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NATURE AND CONTROL OF AIRCRAFT ENGINE EXHAUST EMISSIONS

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NATURE AND CONTROL OF AIRCRAFT ENGINE EXHAUST EMISSIONS

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SUMMARY

This report is the result of a study of the emission of air pollutants by aircraft engines in the United States. The objectives of the study were to:

1. Determine the nature and extent of aircraft engine exhaust emissions.
2. Determine the effects or impact of aircraft engine exhaust emissions.
3. Evaluate approaches to reducing the emission of air pollutants by aircraft engines.
4. Evaluate approaches to governmental control of aircraft engine exhaust emissions.

In achieving each of these objectives, an attempt was made to compile and analyze, as far as possible, all available relevant information. As a result, this report represents our current level of understanding of the nature, impact, and control of aircraft exhaust emissions.

Nature and Extent of Aircraft Engine Exhaust Emissions

Engines used for aircraft propulsion are of two basic classes--piston engines and turbine engines. There are two types of piston engines in common use--opposed engines which are installed generally in light aircraft used for pleasure, business or utility purposes, and radial engines which are in use mainly in older models of transport aircraft. There are three common types of aircraft turbine engines--turbojet, turboprop, and turbofan engines. All are used primarily for propulsion of transport aircraft and medium-size business aircraft. Both piston and

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turbine engines are used for helicopter propulsion.

The exhaust gases from aircraft piston and turbine engines are distinctly different. A turbine engine operates at air-fuel ratios five to twenty times greater than piston engine air-fuel ratios. Consequently, exhaust concentrations of all combustion products are correspondingly less. Also, because of differences in fuels and combustion chamber operation, total quantities of pollutants emitted are different.

Pollutants of concern from aircraft piston engines are the same as those from automobiles: carbon monoxide, organics, oxides of nitrogen, and particulates. As with automobiles, particulates consist primarily of lead compounds. However, the specific physical and chemical characteristics of aircraft lead emissions may differ from those emitted by automobiles. During operations at air terminals, aircraft piston engines are operated at comparatively rich air-fuel ratios. This is particularly true during take-off where rich mixtures are required to obtain maximum power and to avoid engine knock and overheating. As a result, exhaust gases from aircraft piston engines contain comparatively high concentrations of CO and organics, and low concentrations of nitrogen oxides.

Turbine-engine exhaust gases contain the same pollutant types as piston engines--CO, organics, NO_x, and particulates. However, particulates from turbine engines consist mainly of carbon (soot). The detailed composition of organics from turbine engines is not known, but available evidence indicates that they are different in character, and presumably in photochemical reactivity, from organics in piston-engine exhaust gases. During all flight operations, concentrations of CO and organics in turbine-engine exhausts are very low, but during certain ground operations (idle and taxi), these concentrations are higher by factors of 50 to 100. Concentrations of NO_x and particulates, on the other hand, are greater during flight operations, though the variation with power level is not nearly so great as with CO and organic emissions.

Both aviation gasoline and kerosine contain small quantities of sulfur compounds as impurities, and these are emitted in engine exhaust gases as sulfur dioxide. The sulfur content of these fuels, however, is much lower than that of fuels used for space heating and power generation. Consequently, emission of SO_2 by aircraft is only of secondary concern.

Data on aircraft activity, engine fuel consumption and exhaust composition have been assembled and utilized to determine rates of pollutant emission at certain air terminals. Emissions at terminals in the New York City area and at all FAA-controlled terminals in the United States are as shown below:

Pollutant Emission by Aircraft
During Air Terminal Operations

Air Terminals	Aircraft Engine Type	Estimated Average Daily Emission in 1967, 1000 lbs				
		CO	Organics	NO_x	Particulates	SO_2
John F. Kennedy International	Piston	14	2	0.02	0.03	0
	Turbine	53	24	4.8	1.5	1.5
	All types	67	26	4.8	1.5	1.5
Teterboro (General Aviation)	Piston	7	1	0.02	0.02	0
	Turbine	0	0	0	0	0
	All types	7	1	0.02	0.02	0
All FAA-controlled and military terminals in New York City area	Piston	92	11	0.2	0.2	0.02
	Turbine	74	32	7.6	2.7	2.4
	All types	166	43	7.8	2.9	2.4
All FAA-controlled terminals in United States	Piston	4,322	547	7.3	9.0	0.9
	Turbine	807	282	78.2	25.5	28.4
	All types	5,129	829	85.5	34.5	29.3

Emissions from turbine and piston engines are shown separately and reflect the differences in aircraft types utilizing different air terminals.

Estimates have been prepared of pollutant emission in the U. S. by all aircraft including both civil and military aircraft and all operating modes--cruise and air terminal operations. These estimates are shown below along with similar estimates for all motor vehicles:

Annual Pollutant Emission in the U. S.
(Millions of tons per year)

	CO	Organics	NO_x	Particulates	Lead	SO_2
Aircraft	2.4	0.3	0.3	0.03	0.01	0.03
Motor Vehicles	66	12	6	1	0.19	1

Changes in the nature and extent of aircraft exhaust emissions in future years will occur as a result of changes in aircraft activity levels and changes in equipment. Substantial increases in the rates of emission of all pollutants from aircraft engines are expected unless positive steps are taken to reduce these emissions.

Reduction of Aircraft Engine Exhaust Emissions

Methods of reducing pollutant emissions can be categorized as follows:

1. Engine modifications
2. Aircraft modifications
3. Fuel modifications
4. Flight pattern modifications
5. Ground operation modifications

A brief analysis of aircraft and flight pattern characteristics and their relationships with pollutant emission has revealed that categories 2 and 4 do not offer practical approaches to emission reduction. Practical approaches fall in the categories of modifications to engines, fuels, or ground operations.

Certain of these approaches, if utilized, would be effective in reducing certain aircraft emissions from their present levels. Estimates of the potential reductions attainable indicate that CO and organic emissions at air terminals can be reduced substantially by using approaches which are currently feasible. Similarly, a reduction in particulate emission could be expected, though the indicated reduction would be partially offset by increases in aircraft activity. The net effect on particulates would be a reduction of visible smoke, but little change in total emission. The major pollutants for which no effective reduction techniques exist are oxides of nitrogen. The combined effects of equipment changes, reduction of other pollutants, and increased aircraft activity would lead to a rise in NO_x emission. Similar trends exist in NO_x emission from other sources, including automobiles.

Impact of Aircraft Engine Exhaust Emissions

At the present time, two aspects or categories of impact of air pollutants are recognized. The first of these is the exposure of persons or property to concentrations of pollutants which could cause injury or discomfort. The second aspect is the degradation of the atmospheric environment. Whereas the first aspect is concerned with the health of persons and the maintenance of their property, the second is concerned with esthetic values associated with life in an urban community. Aircraft emissions, like pollutants from other sources, are of concern from both standpoints.

Aircraft emissions having the greatest impact are those released during air terminal operations because of the concentrations of aircraft activity and the fact that this activity occurs largely at ground level. Because of this concentration of activity at air terminals, emissions from aircraft are expected to have local effects which differ from their effects on the over-all community.

Pollutant concentrations at air terminals, as indicated by field measurements, are similar to those in surrounding communities. Thus, the impact of aircraft emissions cannot be determined directly because they cannot be distinguished from pollutants from other sources. The local impact of aircraft emissions can be assessed, however, by comparing the density of emissions at air terminals with emission densities in surrounding communities. Such a comparison, shown below, indicates that the densities of emissions of certain pollutants at major air terminals from aircraft alone are comparable to densities of emissions from other sources in adjacent communities.

Density of Aircraft Exhaust Emissions at J. F. Kennedy International Terminal Compared With Emissions in Surrounding Regions

Region	Land Area sq mi	Average Emission Density in 1967 1,000 lb/day per sq mi CO	Organics	NO_x	Particulates
J. F. Kennedy International Terminal	4.5	12.2	4.4	0.44	0.11
Queens County	113	30.2	8.4	5.72	1.10
Kings County	76	25.4	7.2	6.00	2.48

Another basis for comparing the impact of aircraft emissions with those from other sources is provided by calculating pollutant concentrations at air terminals resulting from aircraft operations. Pollutant concentrations from aircraft at air terminals are found to be of the same magnitude as average concentrations from other sources in metropolitan areas.

In future years, quantities of pollutants emitted by aircraft are expected to increase if no emission controls are adopted. Concentrations of these pollutants in air terminal vicinities will increase proportionately. During the next ten years, concentrations of CO, organics, and particulates are expected to increase by 50 to 100 per cent, and NO_x concentrations will increase by a greater amount. Consequently, the impact of these emissions on persons in air terminal vicinities, though perhaps small today, will become more serious in the future.

With regard to the impact of aircraft emissions on community-wide air pollution, the relative contribution by aircraft can be determined by comparing estimates of emission rates from aircraft with rates from other sources. Such a comparison is shown below for the New York City area.

Aircraft Engine Emissions in the New York City Area Compared with Emissions from Other Sources

	CO		Organics	
Source	1,000 lb/day	% of Total	1,000 lb/day	% of Total
Aircraft operations	166	0.6	43	0.6
Ground - All terminals	103		30	
Flight	63		13	
Surface transportation	27,800	95.0	NA	NA
Stationary sources	1,290	4.4	NA	NA
All sources	29,300	100.0	7,780	100.0

	NO_x		Particulates	
Source	1,000 lb/day	% of Total	1,000 lb/day	% of Total
Aircraft operations	7.8	0.2	2.9	0.2
Ground - All terminals	3.2		0.9	
Flight	4.6		2.0	
Surface transportation	NA	NA	189	15.0
Stationary sources	NA	NA	1,070	84.8
All sources	4,210	100.0	1.260	100.0

As indicated, pollutants from aircraft constitute less than 1 per cent of the total quantities of pollutants emitted by all sources in the New York City area. In the future, however, increases in aircraft activity and other factors will bring about substantial increases in aircraft emissions. At the same time, emissions from other sources are expected to be reduced as a result of control measures. It is estimated that contributions of CO and organics by aircraft, if uncontrolled, will increase from current levels of less than 1 per cent to 3 to 5 per cent over a ten year period in certain urban areas.

Certain emissions from aircraft engines are not regarded as hazardous to health, but do produce adverse sensory effects. Such emissions can be regarded as having an esthetic impact. Aircraft emissions in this category are smoke and odor.

Emission of smoke by turbine-engine aircraft has an impact upon the populace beyond its contribution to local and community particulate concentrations. The quantity of solid material in an aircraft exhaust trail is small, but, due to the physical characteristics of this material, it is highly visible even at low densities. The impact of smoke trails, therefore, must be regarded as sensory or esthetic. Nevertheless, smoke must be taken seriously since it is a source of criticism from the public. The fact that its impact has been registered with the aircraft industry is evident from efforts by engine manufacturers to eliminate smoke trails. Results of these efforts will be evident as new civil aircraft engines are put in service.

Odors resulting from the operation of aircraft turbine engines frequently are noticeable in air terminals. These odors are generally objectionable and their presence is regarded as an adverse sensory effect. At present, substances which are responsible for odors from aircraft have not been identified precisely, nor are the mechanisms of odor production well understood. In addition, there are no straightforward methods of measuring odor intensity. The response of human subjects is the only method currently used for measuring odors. Even though odors at air terminals are associated with aircraft activity, it does not necessarily follow that odor intensity is proportional to activity levels. Thus, it is clear that odor represents an effect which should be eliminated, but effective approaches to odor reduction do not exist at the present time.

Control of Aircraft Engine Exhaust Emissions

Two basic approaches to the control of aircraft emissions have been considered. In the first, aircraft would be treated as motor vehicles and subjected individually to emission controls. In the second, an air terminal would be treated as a stationary source and controls would be applied to total emissions from aircraft operations within the terminal area. These approaches are not mutually exclusive. They could be employed jointly to achieve substantial reductions in aircraft emissions. The approaches differ, however, in their suitability for use by different government agencies. The first approach, that of treating an aircraft as a motor vehicle, is best applied by the Federal government. The second approach, that of treating air terminals as stationary sources, is more amenable to use by state, regional, or local governmental agencies.

Approaches which can be taken by the Federal government to reduce the emission or the impact of pollutants from aircraft engines fall into six categories.

a. Specification of exhaust emission standards
b. Regulation of aircraft applications
c. Regulation of aircraft operations
d. Taxation
e. Government procurement
f. Research and development funding

Specification of standards is the most direct approach to exhaust emission reduction. It is being used by the Federal government for the control of emissions from many types of pollutant sources, including automobiles. In the case of aircraft emissions, various pollutant types could be controlled by the application of standards to either engines or fuels. Standards on emission of CO, organics, and particulates could be imposed on new aircraft engines, provided that engine manufacturers were given sufficient lead time to incorporate the necessary modifications in engines currently in production. There is, however, no basis at present for setting a standard on emission of oxides of nitrogen from aircraft engines. Standards could be imposed on aircraft fuels to control emission of SO_2 and lead. Because of the basic similarity of aviation and automobile gasolines, they are amenable to similar standards. Aircraft turbine fuels do not contain lead, and their sulfur content is limited to relatively low values to prevent corrosion of engine elements. The costs associated with further reductions of sulfur content could not be justified.

Regulation of aircraft applications is an approach available to the Federal government through its aircraft certification and registration procedures. These procedures might be useful in the enforcement of emission standards or in providing a basis for pollutant emission taxation, but they offer no unique advantages as primary control measures.

Regulation of aircraft flight operations is an approach which could be used, at least in principle, to reduce emissions at FAA-controlled air terminals. However, emission reductions attainable by this approach are small. Therefore, operational regulation does not offer the Federal government a means to effective pollutant control. On the other hand, control of ground operations could be an effective approach by local government agencies.

Taxation might be utilized to induce the same reductions in emissions which might otherwise be achieved by the establishment of emission or fuel standards. There are two considerations dictating against taxation, however. The first and foremost is that taxation does not assure emission reduction unless tax rates are prohibitively high. The second consideration is that taxation has not been used to date in the United States as an air pollution control method and it would be inappropriate to establish a precedent for taxation by applying it to a minor source of pollutants such as aircraft.

Government procurement has been used by the Federal government as a means for inducing automobile manufacturers to incorporate certain safety features in automobiles. By specifying emission standards for government-purchased aircraft engines, the emission loads from military aircraft could be reduced, and the technology would exist for reducing emissions from civilian versions of the same engines. The Federal government does not purchase significant numbers of aircraft piston engines, and thus, cannot exercise the same leverage in bringing about a reduction in piston-engine emissions. However, the Federal government is a substantial consumer of aircraft fuels, and by this approach could reduce emissions which are associated with fuel composition.

Research and development funding will be necessary to provide the techniques for reducing pollutant emission rates below levels currently attainable. R and D will be required on piston-engine emissions, turbine-engine emissions, and fuel modifications. The Federal government should participate in the funding of such activity.

Classification of an air terminal as a stationary source of air pollutants provides a basis for control of aircraft emissions by local authorities. Control measures would consist of restrictions on aircraft operations, or engine operating time. Criteria for such control measures should be established by the Federal government and based upon differences in engine pollutant emission as determined by standardized measurement techniques. A distinct advantage of this approach is that the degree of control can be varied with time and with terminal location in response to local air quality conditions.

CONCLUSIONS

The principal conclusion drawn from this study is that the nature and extent of air pollutant emission by aircraft in the United States can be assessed from existing knowledge with sufficient accuracy to allow a comparison between aircraft and other emission sources. On this basis, aircraft are a small contributor of pollutants in metropolitan areas. In the vicinities of air terminals, however, the density of pollutant emission by aircraft and the resulting pollutant concentrations are comparable to emission densities and concentrations in adjacent communities of the same pollutants from other sources. Thus, the principal impact of aircraft emissions is local in nature and is expected to become more severe in future years. It is also likely that aircraft emissions will constitute a more significant portion of community-wide pollutant loadings as new aircraft are introduced and as emissions from other sources are reduced. It is further concluded that, whenever a reduction of aircraft emissions becomes desirable, a variety of practicable approaches exist to reducing both the quantities of pollutants emitted and their impact upon the community.

Specific conclusions resulting from this study of aircraft exhaust emissions are as follows:

1. Pollutant Emission
    a. Aircraft exhaust emissions of primary concern include three pollutants emitted as gases or vapors--CO, organics, and nitrogen oxides--and particulate matter consisting mainly of lead compounds or carbon. Sulfur dioxide is emitted by aircraft but is of secondary concern because total quantities emitted are small.

b. Both piston and turbine aircraft engines contribute to significant emission loads of carbon monoxide and organics at air terminals. Turbine engine emissions are most serious during idle and taxi conditions, whereas piston engine emissions of CO and organics are high during all operating modes except cruise. It is possible that afterburning of piston engine exhausts may occur during some operating modes, thereby reducing the effective rates of emission. However, the extent to which afterburning occurs is unknown at present.

c. Emission of oxides of nitrogen by aircraft piston engines is less than that from automobile engines of comparable size or fuel consumption due to differences in operating conditions. NO_x emissions by turbine engines are greater than those from aircraft piston engines, but the aggregate emission load in any urban area is very small compared to that from other sources. Increased NO_x emission is expected from engines currently under development, but the extent of this increase is not known.

d. Particulate emission from aircraft piston engines has not been investigated, but probably consists mainly of lead compounds. The lead content of aviation gasoline is slightly greater than that of automotive gasoline, but the physical state of lead emissions from the two sources may be substantially different.

Particulate emission from turbine engines consists mainly of carbon. Quantities of carbon emitted by turbine-engine aircraft are small compared to those from oil-fired combustion systems, both in terms of pounds-per-pound of fuel and total quantities emitted.

e. Emissions by aircraft in urban areas, if uncontrolled, can be expected to increase with time due to increases in air traffic activity and design changes in aircraft engines. Aircraft activity, in terms of fuel consumption or air terminal operations is expected to increase by nearly 200 per cent during the next ten years, and pollutant emission can be expected to increase proportionately. Engine changes which will affect emissions include the increased use of turbochargers on aircraft piston engines, higher compression ratios and combustion chamber modifications in turbine engines, and replacement of piston engines with turbine engines.

2. Pollutant Impact

a. The density of aircraft emissions at air terminals and the resulting concentrations of pollutants are comparable in magnitude to emission densities and pollutant concentrations in neighboring communities. On this basis, the impact of aircraft emissions on persons in the vicinity of an air terminal is considered to be comparable to the impact on persons in urban areas of emission from other sources.

b. Emissions of all pollutants by aircraft are expected to increase with increases in activity and changes in equipment. The impact of these pollutants in the vicinities of major air terminals also will increase. Whereas the impact of aircraft emissions may be regarded as marginal at the present time, it is expected to become more serious in the near future unless emission controls are adopted.

c. From the standpoint of community pollution, aircraft contribute a small fraction of all pollutants emitted in an urban area. This fraction will become more significant as aircraft activity increases and emissions from other sources are reduced. However, the principal impact of aircraft emissions will continue to be limited to the air terminal vicinity.

d. Pollutant emissions during aircraft flight operations have little impact on the community because the total quantities emitted and the resulting emission densities are small. However, visible trails of particulate matter left by turbine-engine aircraft do have an esthetic impact.

e. Odors resulting from aircraft operations also produce an adverse sensory effect in the vicinities of air terminals. However, practical approaches to the reduction of odors do not exist.

3. Emission Reduction

   a. Reduction of particulate emission by aircraft turbine engines can be accomplished through modifications of engine combustion chambers. Modification techniques have been developed sufficiently to eliminate visible smoke trails.

   b. Reduction of CO and organic emission by aircraft piston engines can be accomplished by replacing these engines with turbine engines, or by incorporating emission control features. Emission control systems most applicable to aircraft piston engines are exhaust treatment systems which have been developed for use with automobile engines.

   c. Reduction of CO and organic emission by aircraft turbine engines can be accomplished through modification of combustion chambers. However, emission reduction methods are not well developed.

   d. No practical methods have been developed for reducing NO_x emission by aircraft piston or turbine engines.

   e. Reduction of CO and organic emission at air terminals can be accomplished by curtailing ground operations of transport aircraft. The most effective technique would involve the use of auxiliary vehicles to tow aircraft or transport passengers.

   f. Fuel modifications do not offer practical approaches to emission reduction except for reduction of lead compounds by piston engines.

g. If all approaches to emission reduction which are presently feasible and practical were put into effect, substantial reductions would result in emissions of CO, organics, and particulates by aircraft. Emission of NO_x, on the other hand, would increase.

4. Emission Control

a. Effective control of emissions of CO, organics, and particulates by aircraft engines could be accomplished by the establishment of emission standards based upon current technology. Measurement techniques are sufficiently well-developed at this time to support the development of standards.

b. Alternate approaches to the control of CO, organic, and particulate emission by aircraft involve the use of taxation and government procurement practices. However, the effectiveness of these approaches is less certain than the use of emission standards.

c. Control of aircraft emissions at air terminals can be accomplished by local authorities by treating air terminals as stationary sources. By this approach, controls on total emissions at air terminals can be established in accordance with local abatement requirements.

RECOMMENDATIONS

The aviation industry is one of the most dynamic areas of commercial activity in this country and in other industrialized nations. The industry is characterized by frequent changes in equipment and services offered, and rapid growth in all categories of flight activity. It also can be characterized as involving relatively large financial investments when decisions are made to proceed with the development of new equipment. Because of these factors, the aircraft industry is particularly sensitive to changes in standards and regulations which affect its operations and utilization of equipment.

At the present time, there are under development several new types of aircraft and many engines which will power these aircraft. In some cases, these aircraft and engines depart considerably in size and performance from equipment in current use. Needless to say, the financial investment in this new equipment is large.

Government control of aviation activity must be considered for several purposes, including safety, noise abatement, and air pollution. At the present time, pollutant emission by aircraft is of less concern than other problem areas. However, it is inevitable that control of aircraft emissions will be instituted at some future time. In order that the imposition of emission controls have the minimum impact on the industry, it is imperative that the Federal Government establish a control philosophy for aircraft emissions as soon as practicable. The early development of an emission control philosophy for aircraft is the first and principal recommendation of this report.

The second recommendation is that the NAPCA encourage and support research and exploratory development in technological areas relevant to aircraft pollutant emission. Continued investigation of the nature, impact, and control of aircraft emissions is warranted in order to provide a sound basis for the establishment of an emission control program.

Specifically, it is recommended that the NAPCA undertake the following program of activity with regard to aircraft emissions:

1. Initiate a program of action to insure that aircraft emissions do not become a serious problem, to include the following elements:
    a. Official recognition of specific aircraft emissions--carbon monoxide, organics, oxides of nitrogen, lead compounds, and other particulates--as potential pollutant problem areas.
    b. Provision of technical guidance and engineering criteria for use by the FAA and/or other regulatory groups at air terminals.
    c. Continued study of approaches to the control of aircraft exhaust emissions, including their effectiveness and impact on the aviation industry.
    d. Monitoring of civil aviation activities, including equipment development, so that significant changes in aircraft emissions can be anticipated.

e. Extension of surveillance by the NAPCA of Federal activities to include aircraft operations.

2. Initiate a program of study of aircraft emissions and their impact to provide the technological basis for future monitoring and control activities. The program should include the following elements:

   a. A study of pollutant emission by aircraft piston engines for the purpose of establishing the actual rates of pollutant emission and the effects of natural afterburning on emissions. This study also should include an evaluation of the effectiveness of exhaust gas treatment systems as applied to aircraft piston engines.

   b. A study of pollutant emission by aircraft turbine engines with particular emphasis on future engine types. The objective of this study would be to determine relationships between engine emission rates and design variables, and to predict the effect of future engine developments on aircraft emission loads.

   c. A study of sampling and analysis techniques for characterizing organic emissions from aircraft turbine engines. The objective of this study would be to develop techniques applicable to exhaust gases containing organic compounds of high molecular weight and low volatility.

d. A study of pollutant emission by aircraft during ground operations at major air terminals. The objective of this study would be to determine quantities of pollutants emitted by all sources during ground operations and to determine the impact of these emissions on persons within and near air terminals. This study also should include an evaluation of techniques for reducing aircraft emissions through modifications of ground operations.

3. Continue studies of pollutant emission problems which are not unique to aircraft engines. Such problems include:
   a. Emission of lead compounds
   b. Emission of odors
   c. Dispersion of emissions from mobile sources such as aircraft

   The need for study of these problems has arisen as a result of pollutant emission from automotive vehicles as well as aircraft. Solutions to these problems, when they are developed, will be applicable to both types of sources.

INTRODUCTION

This report is the result of a study of the emission of air pollutants by aircraft engines in the United States. The study included four aspects of aircraft engine emissions:

1. Nature of aircraft engine emissions and quantities emitted.
2. Effects or impact of aircraft engine emissions on the populace.
3. Reduction of aircraft engine emissions.
4. Governmental control of aircraft engine emissions.

Each of these aspects was investigated and is discussed in this report. In addition, the subject of emission control requirements was considered and a set of guidelines was developed which can be used in determining the degree of control needed. However, specification of control needs, and establishment of a time schedule for control measures were considered to be beyond the scope of this study.

Background

Recognition of motor vehicle engines as major sources of air pollutants evolved generally during the late 1940's and early 1950's and led to widespread investigations of automobile emissions and means for their control. In the late 1950's, automobile engine manufacturers began to incorporate emission reduction features in their products, and, as is well-known, effort to reduce automobile emissions has increased steadily during this decade.

During the 1940's and early 1950's, little attention was given to aircraft as sources of air pollution. A general feeling probably existed that aircraft represented a comparatively small source of pollutants because of their small population, and that control of aircraft emissions was not warranted. This feeling changed abruptly, however, in the late 1950's with the introduction of turbojet aircraft into air carrier service. These aircraft emitted highly visible exhaust plumes during take-off and landing operations, with the densest plumes resulting from the use of water injection during take-off. Exhaust smoke from turbojet engines, coupled with their characteristic fuel odor, brought about a demand for reduction of emissions by jet aircraft. As a result, at least two studies were initiated, one by the Los Angeles County Air Pollution Control District (Ref 1), and another by the Coordinating Research Council, Inc. (Ref 2). In the report of the first study, issued in April, 1960, the authors concluded that "total contaminant emissions from jet aircraft operations are at this time insufficient to produce any generalized deterioration of air quality", and that "visible smoke emissions from commercial jet aircraft...do not constitute violations of opacity standards". The authors also reported a lack of evidence of property damage from aircraft emissions. The report from the second study, also issued in 1960, concluded with the statement that "the relative magnitudes of the emissions from aircraft and from ground vehicles are such that we do not feel that further study is warranted by (this) group". Thus, aircraft emissions were relegated to a status of secondary importance and were not subjected to further investigation during the first half of this decade.

In 1965, the Los Angeles County Air Pollution Control District undertook a second study of aircraft emissions which resulted in a comprehensive report of pollutant emission by all types of civil aircraft in the district (Ref 3). The current (1965) rates of pollutant emission by commercial jet aircraft were found to agree well with projections for 1965 which had been made in 1960 (Ref 1). However, total emissions from aircraft were found to exceed substantially any estimates which had been made previously. This disparity was a result of the inclusion of piston-engine aircraft in this study which, according to the report, were responsible for organic and carbon monoxide emissions far greater than those from turbine-engine aircraft. The report concluded with a comparison of aircraft emissions to those of other sources indicating that aircraft contribute between 1 and 2 per cent of all organic gases, carbon monoxide, and oxides of nitrogen, and approximately 10 per cent of all aerosols (particulates) emitted in Los Angeles County.

The 1965 LAC-APCD report was brought to the attention of the United States Congress in February, 1967 by Mr. Louis J. Fuller, Los Angeles County Air Pollution Control Officer, during hearings before the Senate Public Works Subcommittee on Air and Water Pollution. The subject of these hearings was "Problems and Progress Associated with Control of Automobile Exhaust Emissions", and the LAC-APCD report was included in the record of the hearings. Subsequently, in preparing the text of the Air Quality Act of 1967, the Subcommittee specifically identified aircraft emissions as a subject of concern, and ordered an investigation of this subject by the Department of Health, Education and Welfare.

Methodology

As mentioned previously, the principal aspects of aircraft exhaust emissions of concern in this study are (1) quantities of pollutants emitted, (2) impact of these pollutants, (3) reduction of pollutant emission, and (4) governmental control of pollutant emission. Each of these aspects was investigated in depth and is the subject of a separate section of this report.

To provide a basis for these investigations, background material was gathered which is relevant to aircraft engine emissions and their control. This information includes descriptive material on aircraft and engines, and statistical data on aircraft population, production, activity, and fuel consumption. This information was required for determining the nature and extent of aircraft emissions and for evaluating emission reduction and control, and is summarized in the following three sections of this report. The information in these sections is not necessary for an understanding of the results and conclusions contained in later sections. However, this material has been included to provide the reader with the background data upon which the various investigations were based. This material also provides an introduction to certain aspects of the aviation industry which influence air pollution, and thus, is useful for the reader who is not familiar with this industry.

In the investigation of aircraft emissions and their impact, reduction, and control, effort has been directed primarily toward the emissions resulting from aircraft operations at air terminals. These operations are of concern because the concentration of aircraft activity at air terminals results in localized sources of pollutants within urban areas. These pollutants, in contrast to pollutants emitted during cruising flight, are emitted within a relatively small volume and at low altitude, and as a result, have a greater impact upon persons at ground level. Pollutants emitted by aircraft at high altitude do not affect the populace directly, though there is some concern over possible indirect effects of high altitude emissions.

NATURE OF AIRCRAFT, ENGINES AND FUEL SYSTEMS

It is the purpose of this chapter to introduce certain features of aircraft and their engines and fuel systems which are relevant to pollutant emission. The features of primary concern are those which affect the quantities of pollutants emitted by an individual aircraft during its operations at air terminals.

Aircraft

Classification of Aircraft

For purposes of this investigation, civil aircraft in current use have been classified according to their air pollutant emission potential. The quantities of pollutants emitted by an aircraft during landing and take-off operations are determined by the duration of these operations and the rates of emission of pollutants. The emission rates, in turn, are dependent upon the type of engine (primarily piston or turbine) and its size or power rating. Based on these factors, an aircraft classification system has been formulated consisting of seven classes as described in Table 1. All aircraft within a given class are assumed to emit equal quantities of pollutants (per engine) during air terminal operations. The representative engine for each aircraft class listed in the table is, in most cases, the engine in greatest use in U. S. aircraft of that class.

The classification system described in Table 1 is applicable to most civil aircraft in use in the United States at the present time. Certain military aircraft, such as fighter and attack aircraft, do not fit well into this system. However, activity levels by military aircraft in urban areas are not sufficient to warrant a separate category. Consequently, this system was used for both civil and military aircraft with adjustments made where necessary to account for differences in pollutant emission rates.

Classification of Aircraft Operations

As mentioned previously, aircraft activity of primary interest to this study is that occurring at air terminals. To facilitate an analysis of pollutant emission resulting from terminal operations, an aircraft operational cycle has been defined and termed "landing-take-off cycle" or LTO-cycle. An LTO-cycle includes all normal operational modes performed by an aircraft between the time it descends through an altitude of 3000 feet above the runway on its approach path to the time it subsequently reaches the 3000 foot altitude after take-off. The term "operation" has been avoided because of its use by the FAA to describe either a landing or a take-off. Two operations are involved in one LTO-cycle. An altitude limit was selected in this study, as in previous studies (Refs 1 and 3), which is a reasonable approximation to the meteorological mixing depth over major U. S. metropolitan areas. The implication is that emissions released above 3000 feet do not reach ground level, and that all emissions below 3000 feet have equal impact upon the populace. Actually, the impact of aircraft emissions decreases steadily with altitude, but the 3000 foot limitation is a useful approximation for analysis purposes.

The aircraft LTO-cycle has been divided into six segments or operational "modes", and these have been categorized as ground or flight operations, as follows:

Aircraft Operational Modes

Ground Operations

- Taxi
- Idle
- Landing Run
- Take-off Run

Flight Operations

- Landing Approach (Descent from 3000 feet to touch-down)
- Climb-Out (Ascent from lift-off to 3000 feet)

During each operational mode, engine operating conditions and pollutant emission rates are assumed to remain constant. The modes are grouped according to ground and flight operations to allow for separate study of emissions occuring at ground level and those occurring above ground level. Performance characteristics of aircraft of the various classes during these operational modes are listed in Table 2. Characteristics of interest are mode duration, aircraft velocity, and distance traveled. The methods used to evaluate these characteristics are described in the next section.

Performance Characteristics of Aircraft

The purposes of this section are to describe the characteristics of LTO-cycles for typical aircraft in each of the classes defined previously, and to present the functional dependence of LTO-cycle characteristics upon aircraft characteristics. Typical LTO-cycles are used later in this report to compute pollutant emission loads at air terminals. The relationships between the characteristics of aircraft and the duration of LTO-cycles are used to evaluate means of reducing emissions by changing aircraft design parameters and operating conditions.

It is useful to isolate those characteristics of aircraft that significantly influence the emission of pollutants and their impact at ground level. Rates of pollutant emission by an aircraft engine are only indirectly affected by the aircraft itself. Aircraft performance characteristics affect the duration of the LTO-cycle and the position and velocity of the emission sources (engines) as a function of time. The time spent in the LTO-cycle will influence the total quantity of pollutants emitted, the position of the emission sources will influence the impact of the pollutants emitted, and the velocity of the emission source will influence the quantities of pollutants emitted per unit distance along the flight path.

The times spent by an aircraft in taxi and idle modes are independent of the characteristics of the aircraft itself. During other operational modes, aerodynamic, gravitational, and inertial forces are acting upon the aircraft and affect its velocity and acceleration. During the landing run, an aircraft will also experience decelerating forces from wheel or air brakes and thrust reversal. Only those aircraft characteristics contributing to these forces are considered in this section.

Take-Off Run

During a take-off run, the net accelerating force acting upon an aircraft is the difference between the thrust from the engines and the sum of the aerodynamic and wheel drag forces. The net accelerating force is equal to the product of the aircraft mass and its acceleration. The aircraft will accelerate until a velocity is reached at which the aerodynamic lift is equal to the aircraft weight. At this point the aircraft will lift off.

The take-off distance S may be expressed as

$$S = W^2 / k\ d\ T\ A\ C_{LLO} \qquad (1)$$

where W = aircraft weight

d = air density

T = take-off thrust

A = effective wing area

C_{LLO} = lift coefficient at take-off = $L_{LO} / \frac{1}{2}\ d\ V_{LO}^2\ A$

L_{LO} = aerodynamic lift at take-off

V_{LO} = air speed at lift-off

k is a constant defined by Domasch, et al, (Ref 4) as

$$k = \left[1 - (F_{LO} / F_S)\right] / \ln (F_{LO} / F_S) \approx 0.4 + 0.6\ (F_{LO} / F_S) \qquad (2)$$

where F_{LO} = accelerating force at lift-off

F_S = static accelerating force

If it is assumed that the acceleration is constant, the time to lift-off can be expressed as follows:

$$t_{LO} = 2S/V_{LO} = (W/kT)(2W/C_{LLO}\ d\ A)^{\frac{1}{2}} \qquad (3)$$

Perkins and Hage (Ref 5) show that the distance to clear an obstacle 50 ft high increases the distance given by Equation 1 by 10 per cent for jets and 25 per cent for propeller aircraft. Similar expressions for t_{LO} can be rewritten for propeller aircraft, using equivalent shaft horse power instead of thrust. It should be noted that t_{LO} is shown to be a weak function of wing loading and air density, but linearly dependent upon W/T. Typical values for fully loaded aircraft are given below.

Aircraft Class	Take-Off Time (Minutes)
1	1.0
2	0.8
3	0.4
4	0.6
5	0.6
6	0.4

Assumptions used include zero wind, zero runway slope, and standard day at sea level. Effects of wind speed on the take-off period are small. A 20 knot headwind will decrease t_{LO} by about 5 per cent.

Landing Run

The equations of motion during an aircraft landing run are very similar to those for the take-off run. The major differences are that all external forces acting on the aircraft tend to decelerate it, and the drag components include the effects of braking and thrust reversal. The times spent in the landing mode are, in general, smaller than those in the take-off mode, except for small business jets (class 3) and large piston aircraft (class 5). Comparisons of landing and take-off times are shown in the following table which was prepared from data from manufacturers specifications and Reference 6.

Aircraft Class	Landing Time (Minutes)	Landing Time/Take-Off Time
1	0.4	0.4
2	0.3	0.4
3	0.4	0.1
4	0.3	0.5
5	0.6	1.0
6	0.3	0.75

The relatively long landing time for the Class 3 aircraft may be attributed to an absence of thrust reversal. The corresponding explanation for the Class 5 is not as clear, but could be attributed to a less efficient braking system or to less reverse thrust when the propellers are reversed.

Climb-Out

During the climb-out mode, aerodynamic lift is approximately equal to the aircraft weight, and the net accelerating force (T-D) is equal to the component of aircraft gravitational force which acts along the flight path. These two relationships enable the following expression to be derived for the rate of climb:

$$\text{Rate of Climb} = V_c \left[T/W - 1/(L/D) \right] \qquad (4)$$

where V_c = air speed

L/D = lift-drag ratio

It may be readily seen that the rate of climb increases with increasing thrust to weight ratio and lift-drag ratio.

In many instances, the climb-out mode is regulated by requirements of the FAA and local authorities. Below 10,000 ft in altitude, flight speeds may not exceed 250 knots. Climb-out speed is usually constant at approximately 200 knots for jet aircraft, and noise abatement requirements may restrict engine thrust levels and aircraft speeds further when operating at altitudes between 1000 ft and 1500 ft (Ref 7). However, the time spent in this low-noise mode is a small portion of the total climb-out time to 3000 ft (approximately 1/6).

Typical rate-of-climb data are given for fully loaded aircraft in the following table. These are average values over the first 3000 ft of altitude based upon performance data from aircraft manufacturers, and they do not include noise abatement constraints.

Aircraft Class	Rate of Climb (ft per min)	Time to 3000 ft (min)
1	1365	2.2
2	1580	1.9
3	6000	0.5
4	850	3.6
5	600	5.0
6	1200	2.5

Approach

In practice, the approach path slope is fixed for most aircraft at 3 degrees. The flaps and throttle are set to maintain sufficient velocity and lift to comply with this approach angle requirement. Under these circumstances, the approach velocity and approach time from 3000 ft are given by:

$$V_A = \left[W/\tfrac{1}{2}\, d\, A\, C_{LA} \right]^{\frac{1}{2}} \qquad (5)$$

and

$$t_A = h/V_A \sin a \qquad (6)$$

where h = altitude at start of approach (in this study, 3000 ft)

a = approach path slope

and the subscript A refers to approach conditions. Typical values of approach time, based upon manufacturers performance data, are as follows:

Aircraft Class	Time (min) from 3000 ft
1	3.6
2	3.0
3	1.6
4	4.5
5	4.6
6	3.8

Equations 5 and 6 illustrate that the period spent on approach is a weak function of wing loading (W / A) and approach lift coefficient (C_{LA}).

Helicopters

Helicopters must be considered in a different manner from conventional aircraft because of differences in operational procedures. Helicopters operating in and around urban areas generally fly at altitudes below 3000 ft. Therefore, pollutant emissions from this class of aircraft are of interest, within the context of this study, throughout its complete flight profile. A typical trip of 13 minutes duration has been chosen to represent class 7 aircraft, and this period has been divided equally and assigned to the climb-out and approach operational modes. Helicopters are assumed to spend no time in operations corresponding to the take-off and landing runs of fixed-wing aircraft.

Idle and Taxi

Idle and taxi modes of operation are not directly dependent upon aircraft characteristics. The times spent in these modes depend instead upon airport layout and traffic density. For the purposes of this study, the durations of taxi and idle modes are assumed to be the same for all aircraft, excluding helicopters. Times assigned to these modes are

12 minutes taxiing (6 minutes for helicopters) and 1 minute at idle. These periods are based upon personal observations and correspond to moderate traffic density conditions.

Summary

In this section, it has been shown that the durations of certain operational modes depend upon thrust-to-weight ratio, wing loading, aerodynamic lift coefficient, decelerating power (braking and reverse thrust), and lift-to-drag ratio. The following relationships have been used to evaluate operational mode durations and will be used later to evaluate approaches to emission reduction:

t_{LO} (time to lift-off) $\sim (T/W)^{-1}, (W/A)^{\frac{1}{2}}, (C_{LLO})^{-\frac{1}{2}}$
t_{CO} (climb-out time) $\sim (T/W - 1/(L/D))^{-1}$
t_{A} (approach time) $\sim (W/A)^{-\frac{1}{2}}, C_{LA}^{\frac{1}{2}}$
t_{L} (landing time) $\sim t_{LO}$

The take-off and landing periods also vary with air density, windspeed, and runway slope. The approach period varies inversely with the approach angle. Operational mode characteristics determined by these relationships are summarized in Table 2.

Aircraft Engines

It is the purpose of this section to present a brief description of the two basic classes of aircraft engines--piston and turbine--and the design variations within each class which are in current use. Particular emphasis has been directed toward descriptions of combustion chambers since processes occurring in this part of the engine have the greatest influence on the exhaust composition.

Piston Engines

Classification

Aircraft piston engines are very similar to automobile engines in their manner of operation. The basic engine element is the combustion chamber or "cylinder" wherein fuel and air mixtures are burned and from which energy is extracted through a piston and crank mechanism. Nearly all aircraft piston engines have two or more cylinders, and such engines are generally classified according to their cylinder arrangements (Ref 8). Throughout the history of piston engine development, several cylinder arrangements have been used. However, only two basic arrangements are in general use, these being the opposed and radial configurations.

Opposed (O-type) engines have an even number of cylinders arranged in two opposing rows. The cylinder rows may be arranged vertically, such an engine being termed vertically opposed (VO-type), or the rows may be horizontal as in the more common horizontally-opposed (HO-type) engine. Four and six-cylinder engines are most common, but two and eight-cylinder engines are available. Engine power levels range approximately from 60 to 400 horsepower. An important performance characteristic of an aircraft piston engine is its power-to-weight ratio. The value of this parameter for O-type engines currently in production varies between 0.55 and 0.73 take-off horsepower per pound as compared to values of 0.4 or less for most automobile engines. Opposed piston engines are produced in large numbers and are installed in most light aircraft.

Radial (R-type) engines are constructed with cylinders arranged in circular arrays or "banks". Each bank contains an odd number of cylinders, usually 7 or 9, and the pistons in one bank of cylinders are joined to a common connecting rod assembly. Most radial engines consist of 1 or 2 cylinder-banks. However, one four-bank, 28-cylinder engine - the Pratt & Whitney R-4360 - is in service in certain military transport aircraft. Power levels of radial engines range from 250 to 3800 horsepower, and their power-to-weight ratios vary from 0.5 to 1.05 take-off horsepower per pound. Radial piston engines have been used extensively in transport aircraft, but are being replaced rapidly by turbine engines.

Operating Characteristics

Processes occurring in an aircraft piston engine combustion chamber are similar to those of an automobile engine. The operating cycle consists of 4 strokes - intake, compression, power, and exhaust - with a complete cycle occurring during two revolutions of the crankshaft. A mixture of fuel-vapor and air is drawn into the chamber during the intake stroke and is compressed during the compression stroke. The mixture is ignited by a spark at the beginning of the power stroke and, as a result of the pressure increase from combustion, power is transmitted through the piston to the crankshaft. During the exhaust stroke, the combustion products are expelled to the exhaust system.

Even though the aircraft piston engine is similar in operation to the gasoline-fueled automobile engine, certain differences between the two are worthy of mention as they may result in differences in exhaust gas composition.

1. Air induction system. Many medium and large piston engines use a supercharger, or "blower", to increase the engine operating pressure and thereby increase the power output.

Super-chargers are driven mechanically by the engine or by a turbine (turbocharger) driven by the engine exhaust gases. With a turbocharger, the engine is operated highly fuel-rich during certain modes in order to maintain the exhaust gas temperatures below a level which would cause damage to the turbine. Fuel-rich operation occurs mainly during take-off and climb-out when high engine power is required.

2. Fuel metering system. As with automobiles, most small aircraft engines utilize a float-type carburetor which meters fuel into the intake air upstream from the distribution manifold. However, most large engines and a significant number of smaller engines use a fuel-injection system which meters the fuel individually to each cylinder. Fuel injection provides greater uniformity in fuel-air ratio from cylinder to cylinder.
3. Ignition system. Nearly all aircraft engines have dual ignition systems, including two spark plugs per cylinder. The dual system provides more reliable ignition and, thereby, a lower rate of ignition failure. The ignition failure rate in automobile engines is high, particularly at high speeds.
4. Exhaust system. Aircraft engine exhaust systems differ from those of automobile engines mainly in the exhaust stack length. The short stack length results in a higher exhaust gas temperature which increases the possibility of afterburning, that is, spontaneous combustion of fuel-rich exhaust products with air after emission from the stack.

5. Cooling system. Nearly all aircraft piston engines are air-cooled in contrast to automobile engines of which the majority are water-cooled. Air-cooling results in higher cylinder wall temperatures which may affect combustion product composition. However, to the knowledge of the authors, no relationship between these factors has been observed to date.

The crankshaft of a small, aircraft piston engine usually is connected directly to the propeller shaft. Medium and large piston engines, on the other hand, generally transmit power to the propeller through a system of gears such that the propeller speed is less than that of the engine. The requirement for gearing stems from the desirability of maintaining propeller tip-speeds at subsonic levels.

Turbine Engines*

Classification

There are four basic types of gas turbine engines used for aircraft propulsion: turbojet, turboprop, turboshaft, and turbofan engines. The basic element of all turbine engines is the gas turbine, consisting of a compressor, a combustion chamber, and a turbine. Air enters the forward end of the engine, is compressed by the compressor, is heated by combustion of fuel in the combustion chamber, and expends part of its energy in driving the turbine which, in turn, drives the compressor. The remaining energy in the air stream is used for aircraft propulsion.

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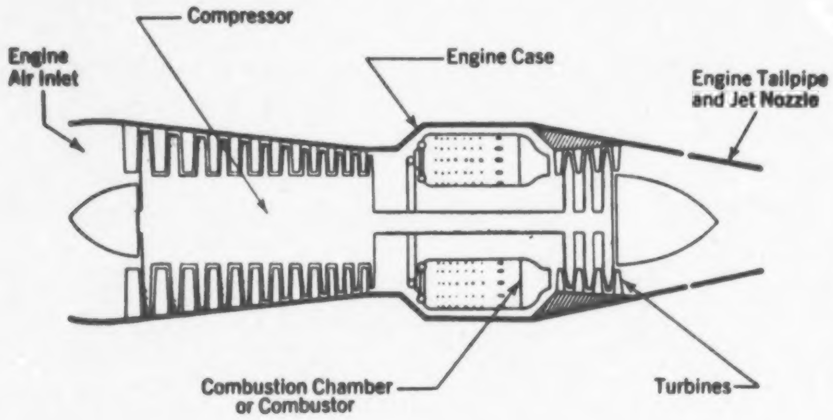
Turbojets

When used as an aircraft power plant, a gas turbine is provided with a tailpipe and jet nozzle, which makes it a turbojet. Turboprops, turbofans, and gas-turbine engines that turn a shaft for helicopter use are more sophisticated versions of the basic gas turbine. These engine types will be discussed later. For the moment, let us consider only the uncomplicated turbojet.


Compressor
Engine Air Inlet
Engine Case
Engine Tailpipe and Jet Nozzle
Combustion Chamber or Combustor
Turbines

Externally, a turbojet engine somewhat resembles a large, irregularly-shaped piece of stovepipe open at both ends. Huge quantities of air enter the engine at the front and exhaust, greatly heated and accelerated, through a big hole at the rear. The forward part of the engine shell, or case, houses a compressor that squeezes and compresses the incoming air before passing it on to a burner section, or combustion chamber. The fuel is sprayed through nozzles into the front of the combustion chamber. The resulting mixture of fuel and air is burned to produce hot, expanding gases that rush to the rear of the engine where they are exhausted to the outside through a short duct called the engine tailpipe. The opening at the rear of this pipe, or exhaust duct, is called a jet nozzle.

Before the gases enter the engine tailpipe, they pass through a turbine mounted directly behind the combustion chamber. Their high velocity causes the turbine to rotate. The power the turbine extracts from the gases is used to drive the compressor. The turbine and the compressor are both mounted on the same shaft and rotate as a single unit, so it might be said that a single-compressor turbojet engine has only one major moving part.

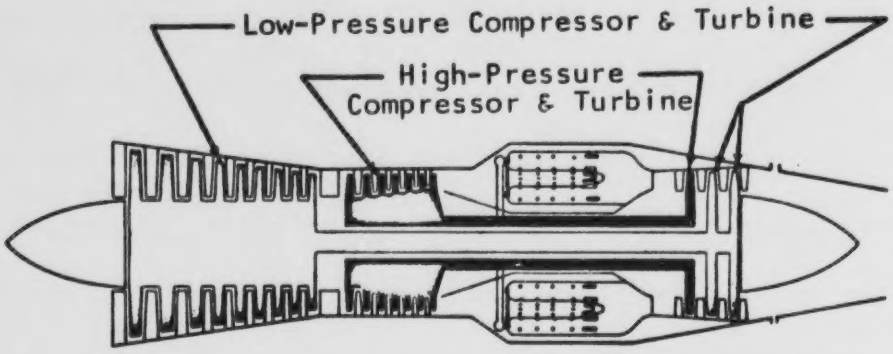
Turbojets are classified according to the kind of compressor they use. For years, they had only centrifugal compressors because this was the type that designers knew best how to build. Centrifugal compressors operate by taking in air near a hub at the center and rotating it with an impeller.

As the impeller whirls the air at high speed, centrifugal force carries the air to the perimeter of the impeller at a considerable velocity. Here the air is collected in a diffuser to increase the pressure, then led to a manifold which, in turns, feeds it to the engine's burners.

The early centrifugal compressor turbojets were (and still are) both reliable and simple. But the amount of thrust they can produce is relatively low because their compression ratio is not very high. Nevertheless, there are several turboprop and turboshaft engines now in current production that employ a compressor arrangement using one or more centrifugal-type compressors. The improved design of these engines makes them far superior to the centrifugal-compressor power plants of several years ago.

The majority of today's turbojets use an axial compressor like those which are illustrated. Axial compressors are used, especially in the larger engines, because they are capable of producing high compression ratios, sometimes as high as 13:1, or more. An axial compressor, as the name implies, compresses air as it flows in an axial direction, through an engine. A series of rotating blades and stationary vanes work on the air as it passes through a series of stages inside the compressor. Each stage adds to the compression process.

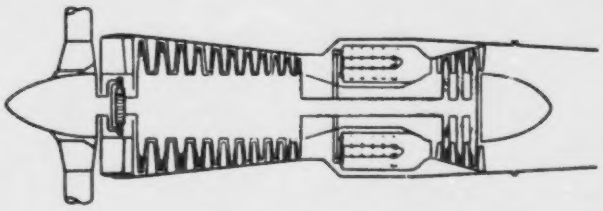
There are two types of axial-compressor engines, those with so-called single compressors and those with dual compressors. In dual-compressor engines (sometimes called twin-spool engines), there are two compressors that are mechanically independent of one another, although they are related as to airflow. Each compressor has its own turbine. The turbine for the forward, or low-pressure compressor, is the rear turbine. It is connected to the low-pressure compressor by a drive shaft that passes through the hollow drive shaft for the high-pressure compressor and turbine unit.


Low-Pressure Compressor & Turbine
High-Pressure Compressor & Turbine

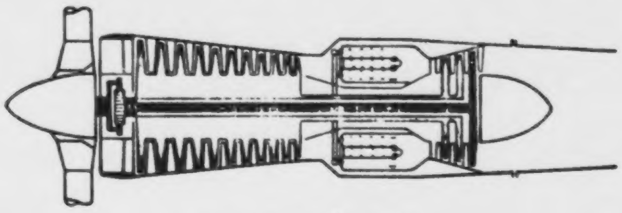
Dual-Axial Compressor Turbojet

Turboprops

If a gas turbine turns an aircraft propeller through a system of gears, it becomes a turboprop. The British and many commercial airlines call such an engine a propjet. The propeller-drive reduction gearing may be driven by the shaft from the same turbine that rotates the compressor, or the gearing may be driven by a shaft from a so-called free turbine that rotates independently in the exhaust gas stream of the basic gas turbine. In either case, the gas turbine for a turboprop might be either a single or a dual-compressor type, although, as this is written, there are no dual-axial compressor turboprops in production. There are, however, a number of turboprops whose compressors have novel arrangements. One of these is the Rolls Royce Dart, which employs two centrifugal compressors in tandem. Other successful turboprops have axial compressors with a centrifugal compressor immediately following. These engines are also produced in turboshaft configurations.

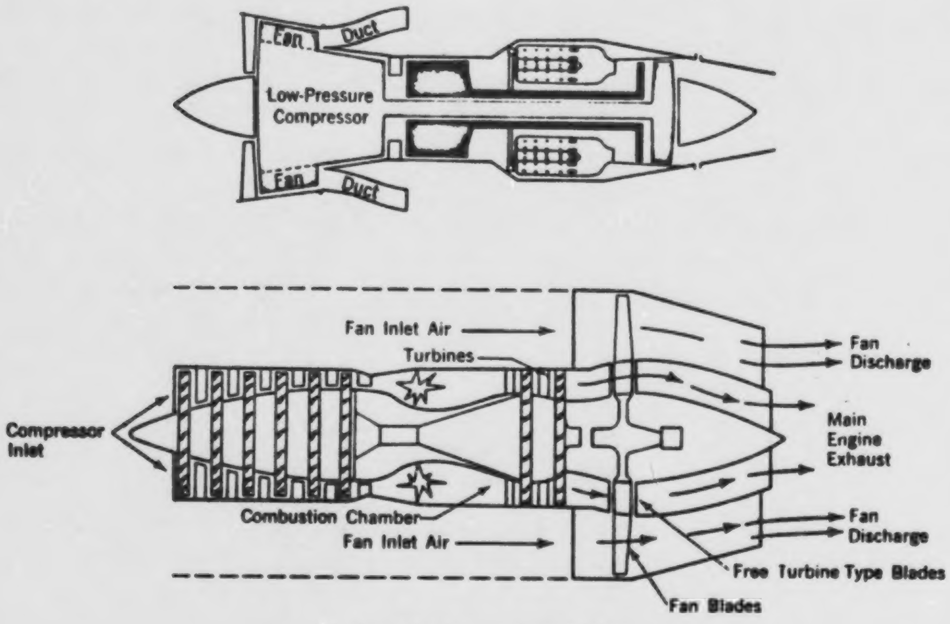


Single-Axial Compressor, Direct-Drive Turboprop



Single-Axial Compressor, Free Turbine-Drive Turboprop

Although a turboprop is more complicated and heavier than a turbojet engine of equivalent size and power, it will deliver more thrust up to medium-high subsonic airspeeds. However, the advantage decreases as flight speed increases. In normal cruising-speed ranges, the propulsive efficiency (output divided by input) of a turboprop remains more or less constant, whereas the propulsive efficiency of a turbojet increases rapidly as airspeed increases. The spectacular performance of a turboprop during take-off and climb is the result of the ability of the propeller to accelerate a large mass of air while the aircraft is moving at relatively low ground and flight speed.


Fan
Duct
Low-Pressure Compressor
Fan
Duct
Fan Inlet Air
Turbines
Compressor Inlet
Combustion Chamber
Fan Inlet Air
Fan Discharge
Main Engine Exhaust
Fan Discharge
Free Turbine Type Blades
Fan Blades

Single-Compressor, Aft-Fan Engine

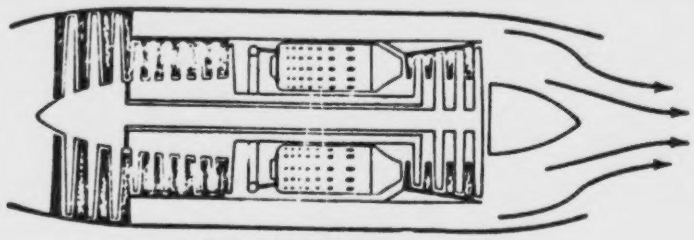
Turbofans

Fanjets, as they are called by some of the commercial airlines, and turbofans are one and the same thing. In principle, the turbofan (or fanjet) is the same as the turboprop except that the ratio of the secondary airflow (i.e., the airflow through the fan or propeller) to the primary airflow through the basic engine is less. Also, in the turbofan, the gear-driven propeller is replaced by a duct-enclosed, axial-flow fan whose rotating blades and stationary vanes are considerably larger but otherwise similar to the blades and vanes of an axial compressor.

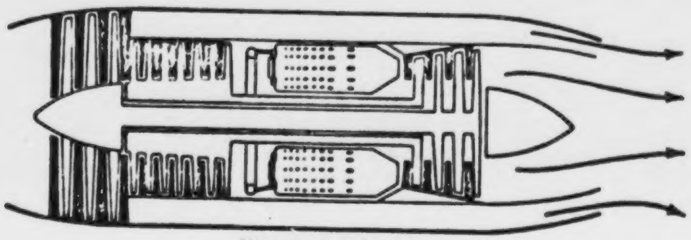
There are two principal configurations for a turbofan, each of which has several variations. In one configuration, the fan is placed at the front of the engine where it is an integral part of the compressor. When the engine is a dual-compressor type, it is a part of the forward, low-pressure compressor. In the other configuration, the fan is mounted at the rear of the engine where it forms the rim, or outer perimeter, of a free turbine that rotates by itself in the exhaust gases discharged from the engine. These two turbofan designs are called forward fan and aft fan engines, respectively.

In both turbofan configurations, the fan makes a substantial contribution to the total thrust. Over and above the thrust produced by the basic engine, the fan accelerates the air passing through it to generate thrust of its own in the manner of the propeller of a turboprop. The fan air is exhausted without passing through the engine; it is not burned with fuel or used for internal engine cooling.

Two different duct designs are used with forward-fan engines. Either the air exhaused by the fan may be ducted overboard directly after it leaves the fan, or it may be ducted along the outer case of the basic engine to mix, or not mix (depending upon the design), with the turbine exhaust gases before the gases pass through the jet nozzle.



Forward Turbofan With Mixed Exhaust



Nonmixed Exhaust

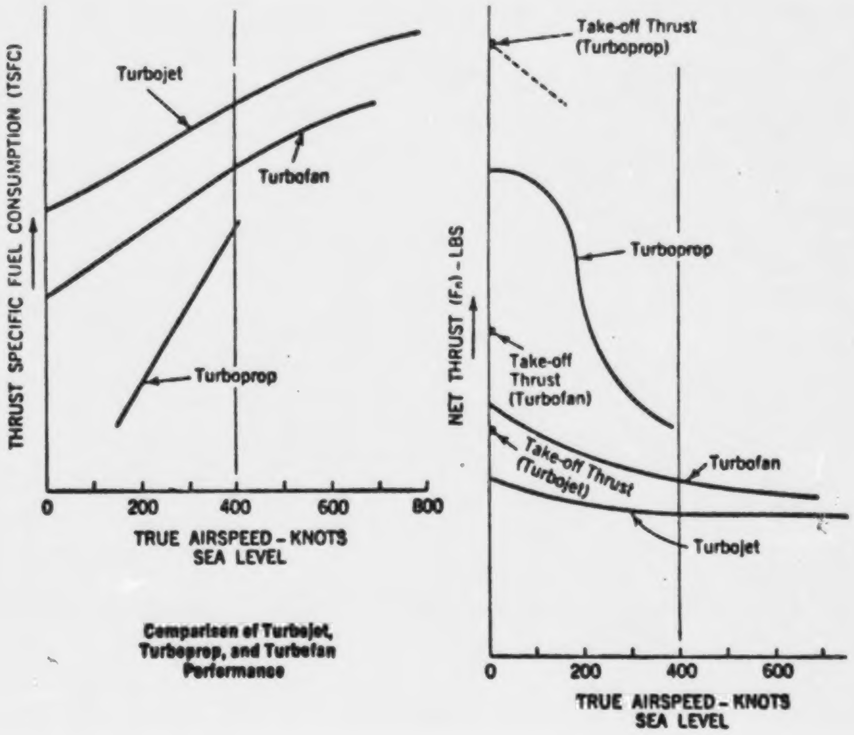
One fundamental difference between a turbofan and a turboprop is that the airflow through the fan is controlled by the design of the engine in such a manner that the air velocity through the fan blades is not affected very much by the speed of the aircraft. This means that the loss of operational efficiency at high air speeds that limits the airspeed capability of turboprop aircraft is eliminated in turbofan aircraft. Indeed, supersonic aircraft not only can, but are being powered by turbofans. The military F-111, an all-purpose, fighter-type airplane that attains speeds in excess of Mach 2.0, is a typical example.

Turbofans are rapidly becoming the most widely used of all the types of jet engines, particularly in large multi-engine aircraft. The turbofan is, in effect, a compromise between the good operating efficiency and high-thrust capability of a turboprop and the high speed, high-altitude capability of a turbojet. At cruising altitude, the engine-propeller combination of a turboprop loses efficiency rapidly at airspeeds above 400 knots. Not only does the turbofan have no such limitation but it is much simpler than a turboprop. The complexity and weight of the propeller reduction gearing and the intricate propeller-governing feature of a turboprop are completely eliminated in a turbofan. The turbofan is therefore not only lighter than a turboprop but can never be plagued by any of the malfunctions to which a propeller and its associated systems are susceptible.

The fact that the fan air does not pass through the basic engine enables a turbofan to achieve a relatively low specific fuel consumption. In addition, because it accelerates a large mass of air to relatively low velocity, even at very low aircraft speeds, a turbofan, like a turboprop, produces much more thrust than a turbojet during take-off and the initial climb.

Another advantage of the turbofan is a lower noise level, which is an important feature at all commercial airports. The lower level of noise occurs because a turbofan engine has at least one additional turbine stage to drive the fan. Extraction of more power from the engine exhaust gases as they pass through the additional turbine (or turbines) serves to reduce the velocity of the engine exhaust. Less velocity through the jet nozzle results in less noise.

Note: In the curves shown, all performance data has been reduced to a common denominator, thrust in pounds. The engines used to make this comparison are actual engines that use the same basic gas turbine, and the curves have been plotted from actual performance data.

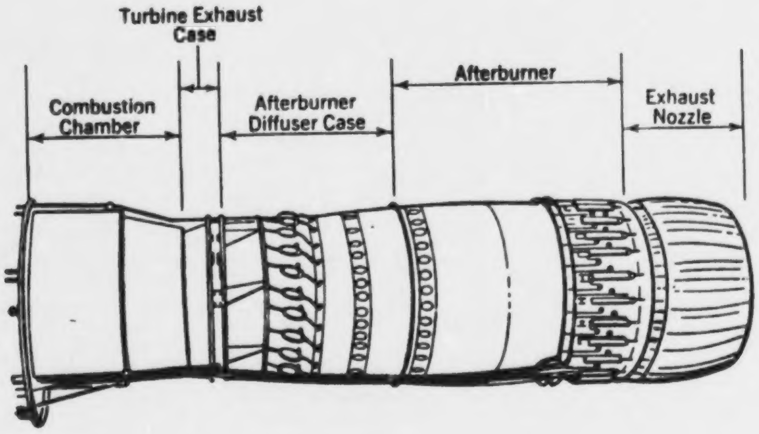


Comparison of Turbojet, Turboprop, and Turbofan Performance

Afterburning Turbojets and Turbofans

Frequently, an engine is provided with an afterburner for increased thrust. The British say that afterburning is "reheating" and they call an afterburner a "reheater." The increased thrust that comes with afterburning can be accomplished regardless of the type of compressor and regardless of whether the engine is a turbojet or a turbofan.

Only about 25 per cent of the air entering an engine at the compressor inlet is used to support combustion; the rest is used for internal cooling in the main part of the engine, before it passes out the tailpipe. Essentially, an afterburner is an enormous piece of stovepipe attached at the rear of the engine in lieu of a tailpipe and jet nozzle. Fuel is injected through fuel nozzles and ignited in the forward section of the afterburner. Combustion is possible because 75 per cent of the air entering the afterburner, no longer needed for cooling, is still unused for combustion. As the excess air and the added fuel burn together in the



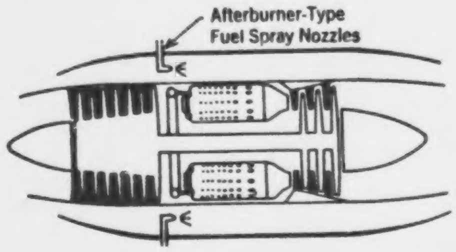
afterburner, the exhaust gases are again expanded and accelerated which, in turn, means more thrust. The afterburner is provided with flame holders to prevent the flame from being blown out of the exhaust and with a two-position, variable-area exhaust nozzle that is fully closed when the afterburner is not in use. The nozzle opens automatically when the afterburner is turned on.

An afterburner is capable of increasing the total engine thrust by 50 percent, or more. Although the total fuel consumption more than doubles, the net result is profitable for bursts of aircraft speed such as a much faster climb or an acceleration to supersonic flight. By climbing rapidly with the afterburner on, a jet-powered airplane will use less fuel in reaching a given altitude than it will by climbing more slowly without the afterburner. But the weight and noise of an afterburner which, on long flights, might be used only occasionally, precludes the device being employed in present-day, transport-type airplanes and commercial aircraft. Afterburners are presently used only on military fighters and supersonic bombers.

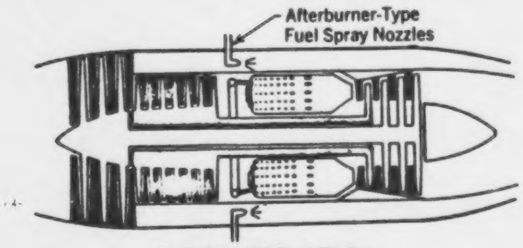
Miscellaneous Jet Engine Types

Turboshaft Engines: Turboshaft engines are closely related to turboprops. If a gas turbine engine delivers power through a shaft that operates something other than an aircraft propeller, the power plant is called a turboshaft engine. Like the propeller drive shaft of a turboprop, the shaft may be coupled to the engine's turbine directly, through a system of reduction gears, or the shaft may be driven (also through reduction gears) by a free turbine of its own in the exhaust-gas stream. Engines of this type are used in helicopters.

Bypass Engines: In Great Britain, forward-fan turbofans of the mixed and non-mixed exhaust types are called bypass engines, the Rolls Royce Conway being a typical example. In this country, a bypass engine is generally considered to be an engine in which the secondary airstream is subject to ram pressure only. In effect, this means a ramjet engine built around the outer case of a turbojet. This is a configuration not in current use.



Bypass Engine
(American version)



Turbofan With Duct Heater

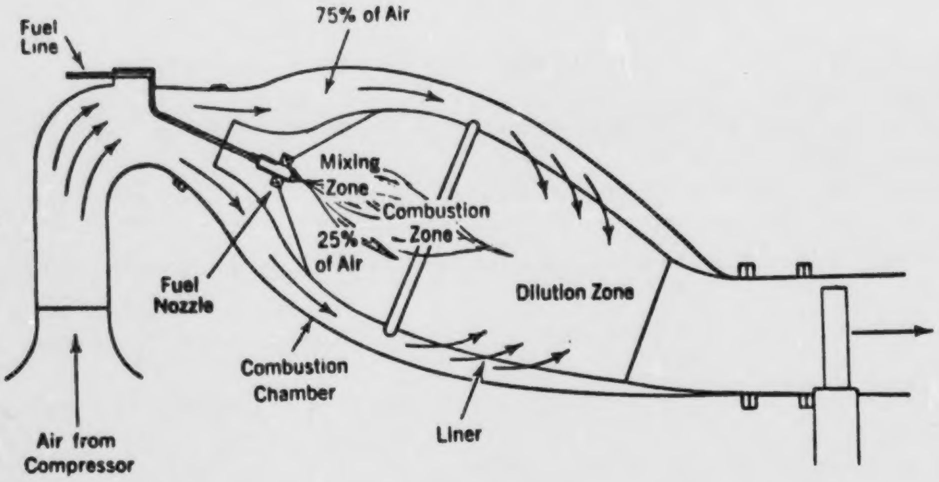
Engines with Duct Heaters: If an afterburner-type fuel nozzle and flameholder arrangement were to be placed in the open duct of a turbofan engine with a non-mixed exhaust, the device would be called a duct heater and it would operate like an afterburner. The air in the duct would be burned with fuel to increase the momentum of the air and gases passing through, thus producing more thrust. Engines with duct heaters are not in production now, but the design has been investigated and may be used someday.

Combustion Chamber Operation

The burner section of a turbine engine, which contains the combustion chamber, is designed to burn a mixture of fuel and air, and to deliver the resulting gases to the turbine inlet at a temperature that will not exceed the maximum permissible. The burner section, within a very limited space, must sufficiently heat and expand the gases passing through the engine to produce the desired thrust for the engine and power for the turbine. In a jet engine, the fuel nozzles, the air and fuel mixing vanes, and the combustion chamber are so skillfully designed that the heat released per cubic foot of combustion space is about one thousand times as great as the heat released in an equivalent burner space in an ordinary home-heating furnace.

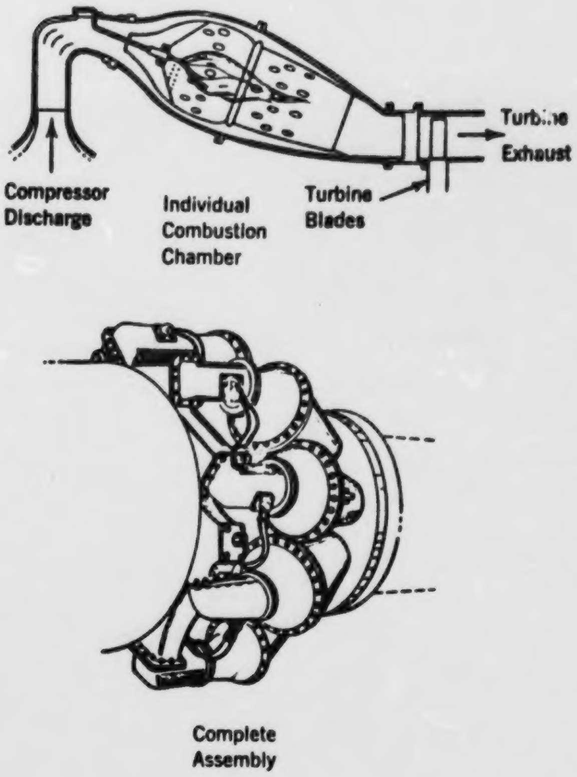
The burner has a big job to do. With only a minimum drop in pressure, it must provide the correct amount of air at the proper point in combustion chamber to support combustion under all operating conditions; it must provide the combustion air with the proper flow patterns to assist the burning process; and it must provide unburned air at the proper places and in the proper quantity to establish a cooling layer of air on the inside of the combustion-chamber liner. The burner must also supply air to mix with the burned gases and thereby reduce the temperature at the turbine inlet. Fortunately, a burner which can satisfy all of these conditions will also have satisfactory engine starting characteristics.

Combustion chambers may be either of the can, the annular, or the so-called can-annular type. For all of these, the design is such that only about 25 per cent of the total volume of air entering the chamber is permitted to mix and burn with the fuel. The remaining 75 per cent bypasses



the fuel nozzles and is used to cool the combustion-chamber liner and to mix with and cool the burner gases before they enter the turbine.

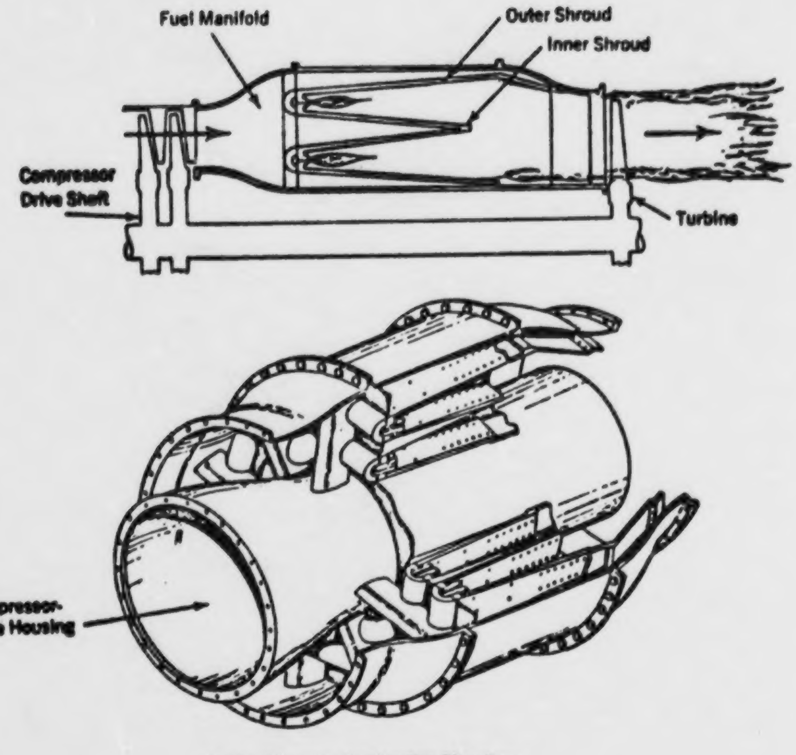
Multiple Can-Type Combustion Chamber: An arrangement of can-type combustion chambers is usually found on the older type centrifugal-compressor turbojets. In a burner section of this kind, the air from the compressor is divided as it leaves the diffuser and ducted to the individual combustion cans, or chambers, which are arranged around the circumference of the burner section of the engine. Each can contains its own fuel nozzle and combustion-chamber liner. Primary air (air for burning) is introduced at the nozzles where it serves to support the initial phase of the burning process. Cooling, or secondary, air passes between the liner and the combustion-chamber case. The liner is provided with several series of holes or axial slots through which some of the secondary air enters the burning chamber to help support the combustion process. The holes or slots also furnish a layer of cooling air which flows down the inside of the liner to cool the inside surface. After combustion is completed, the burned gases and the surplus heated air that was used for cooling merge, just upstream from the entrance to the turbine. This reduces the temperature of the burned gases to a level that the turbine can tolerate.


Turbine
Exhaust
Compressor
Discharge
Individual
Combustion
Chamber
Turbine
Blades
Complete
Assembly

Multiple Can-Type Combustion Chamber

Annular Combustion Chamber: Some axial-compressor engines, the smaller models in particular, have an annular combustion chamber. The liner of this type of chamber consists of continuous, circular, inner and outer shrouds around the outside of the compressor-drive housing. The liner is sometimes referred to as a burner basket because it is perforated with holes which give it a basket appearance. The holes or slots in the shrouds allow secondary cooling air to enter the combustion area, thereby keeping the flame away from the shrouds. Fuel is introduced through a series of nozzles at the upstream end of the liner.

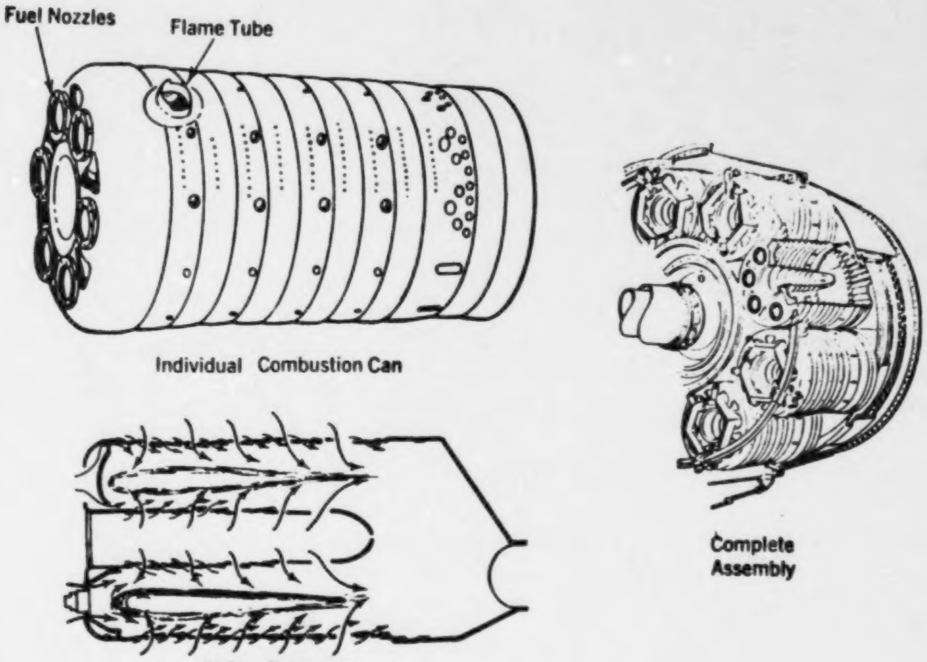
Annular combustion chambers are able to use the limited space available within the burner section to better advantage than any other kind of chamber. An optimum ratio of the inner surface area of the liner to the volume of the chamber is provided, ensuring maximum cooling of


Fuel Manifold
Outer Shroud
Inner Shroud
Compressor Drive Shaft
Turbine
Compressor-Drive Housing

Typical Annular Combustion Chamber

the gases and the liner surfaces as combustion takes place. The design is strong enough to prevent the heat within the chamber from warping the liner, a problem in other types of chambers. But this is offset by the fact that the liner cannot be replaced or repaired without removing and disassembling the engine.

Can-Annular Combustion Chamber: A can-annular, combustion-chamber design is used on many of the larger jet engines. Individual burner cans are placed side by side in an annular chamber. The cans are essentially individual combustion cylinders with concentric rings of perforated holes to admit air for cooling. On some models, each can is provided with a round, perforated tube which runs down the middle of the can. The tube carries additional air which enters the can through the perforations to provide more air for burning and cooling. The effect is



Individual Combustion Can

Complete Assembly

Airflow Schematic

Can-Annular Combustion Chamber

to permit more burning per inch of can length than could be accomplished otherwise.

Several fuel nozzles are placed around the perimeter of the forward end of the can. The burner cans are relatively small in diameter, which gives them an inherent resistance to the buckling caused by heat. Each can has two holes which are opposite each other near the forward end of the can. One hole has a collar called a flame tube. When the cans are assembled in the annular chamber, these holes and their collars form open tubes from can to can so a flame in one will pass to the others during engine starting.

The can-annular combustion chamber combines the advantages of both the can and the annular combustion-chamber designs. It also eliminates many of their disadvantages. A removable or telescoping shroud covers the entire burner assembly. This permits easy access to the individual cans, which may be removed for inspection and replaced without removing the engine.

Fuel Systems

Aircraft fuel systems are of interest to this study primarily because they control the rate of flow of fuel to the aircraft engine and the physical state of the fuel as it enters the combustion chamber. These factors, in turn, affect the rate of production of pollutant species in the engine. The fuel system also is of interest as a source of pollutants - primarily unburned fuel. However, sources other than engine exhausts have not been included in this study.

The main function of a fuel system is to transport fuel in sufficient quantity and with sufficient quality and pressure to satisfy engine requirements under all operating conditions. A secondary function that will become of increasing importance in supersonic aircraft is the use of fuel as a coolant for other aircraft systems. The complexity of a fuel system depends, therefore, upon both the aircraft performance and the type of engine installed.

The principal components of fuel systems for piston-engine and turbine-engine aircraft are shown in Figures 1 and 2. These systems have certain common components: fuel tank, fuel strainer, fuel pump (except for gravity-fed systems), and a fuel control unit. The function of each of these components is the same in each fuel system.

The fuel control unit is of interest from the standpoint of air pollutant emission. This unit controls the fuel flow rate and the fuel-air ratio to the engine. In a turbine-engine fuel system, the fuel control unit is a complex, mechanical, computer-type device. It is programmed to supply the correct fuel rate in response to engine operating conditions and throttle setting. The fuel control unit for a piston engine is less complex and consists of either a carburetor or a fuel-injection control device similar to units used in automotive fuel systems. These devices also respond to engine operating conditions and throttle setting. There is, however, an additional manual adjustment incorporated in piston-engine fuel systems known as the mixture control. The mixture control allows the fuel rate and fuel-air ratio to be changed manually by the pilot. In practice, this control is set at "full rich" during air terminal operations to provide maximum engine power and to prevent overheating. During cruising flight, the mixture control usually is adjusted to provide leaner, more economical, fuel-air mixtures. Because of this practice, aircraft piston engines operate at comparatively rich fuel-air ratios during all air terminal operations, and, as a result, their exhaust gases contain higher concentrations of carbon monoxide and unburned fuel than automobile exhausts. This fact is significant from the standpoint of air pollution. The fact that the engine fuel-air ratio is manually controlled by the pilot also is significant. The pilot of a turbine-engine aircraft has no corresponding control which affects the rate of pollutant emission from his engines. The significance of the manual mixture control in piston engines and their rich fuel-air mixtures will be discussed in later sections dealing with pollutant emission and emission reduction.

The methods used to inject fuel into engine combustion chambers are different in piston and turbine engines. In piston engines, fuel is injected into the air intake manifold where it is vaporized before entering the cylinders. The fuel-air mixture is nearly homogeneous prior to ignition. The injection system, therefore, has little direct effect on the combustion process or the nature of the exhaust products, except that non-uniform injection can cause variations in fuel-air ratio and pollutant emission rate among cylinders.

In turbine engines it is currently the practice to spray the fuel in atomized form into the combustor and to allow vaporization and combustion to proceed simultaneously. This practice creates many practical difficulties and the design of spray nozzles has changed many times over the years.

The characteristics of the fuel spray affect combustor efficiency, ease of ignition, combustor wall heating, and various other problems associated with engine performance. In addition, the nature of the fuel spray affects the formation of pollutant species within the combustor - particularly smoke.

It is difficult to develop a fuel nozzle with spray characteristics which are satisfactory over the wide range of fuel flow rates encountered in a turbine engine. Most engines use a dual-orifice, pressure nozzle similar to that shown in Figure 3 which operates from two independent fuel manifolds. Much attention is currently focussed upon the method of fuel injection, however, and attempts are being made to utilize injectors which provide some fuel vaporization before combustion. An example of such an injector is the airspray fuel atomizer also shown in Figure 3. It is believed that a significant reduction in smoke emission can be achieved through the use of such injectors, and they are being incorporated in engines currently in development (Refs 12 and 13).

Summary

In this section, certain aircraft systems have been described which affect the emission of air pollutants in engine exhaust gases during aircraft operations at air terminals. These systems are the aircraft structure or airframe, its engines, and its fuel system. These systems affect both the duration of landing and take-off operations and the rates of pollutant emission during these operations. The mechanisms of pollutant formation, rates of emission, and emission reduction methods will be discussed in later sections of this report.

There are other sources of air pollutants associated with aircraft operations which have not been included in this investigation. These sources add to the total quantities of pollutants emitted during air terminal operations and include:

(1) Exhaust gases from aircraft auxiliary power units.
(2) Exhaust gases from service vehicles.
(3) Evaporative losses from aircraft fuel systems.
(4) Evaporative losses from fuel storage and transfer equipment.
(5) Organic emissions from various servicing materials including paint, solvents, lubricants, and deicing agents.

Sources such as these should be included in future studies of pollutant emission at air terminals.

AIRCRAFT AND AIRCRAFT ENGINE POPULATION, PRODUCTION, AND ACTIVITY

It is the purpose of this chapter to present certain statistical data on aviation in the United States which are relevant to air pollution. Data on aircraft population, production, and activity are important in assessing the nature and quantities of aircraft exhaust emissions, and in evaluating approaches to the reduction of exhaust emissions and their impact. Information contained in this chapter has been taken mainly from publications of the United States Federal Aviation Administration, the United States Civil Aeronautics Board, and the Aerospace Industries Association of America, Inc.

Aircraft and Aircraft Engine Population

Civil Aircraft Population

Civil aircraft of interest to this study are those which are approved for use in regular service in the United States. Such an aircraft must be registered with the FAA and have a current FAA air-worthiness certificate. The latter is obtained through annual or continuing inspection. A registered, certificated aircraft is designated by the FAA as "eligible", whereas a registered, but uncertificated, aircraft is designated "ineligible".

The numbers of registered aircraft of various types are shown in Table 3 for 1967. The total number of eligible aircraft in 1967 (107,085) increased by 9344, or approximately 10 per cent, from the previous year. The total number of eligible turbine-powered aircraft, however, increased from 1624 to 2286 during 1966, representing an increase of approximately 40 per cent. It is apparent that turbine-powered aircraft, even though constituting only 2 per cent of the current population of civil aircraft, will occupy a larger fraction of the total in ensuing years.

Future projections of civil aircraft population, as published by the FAA, are listed in Table 4. The projections indicate an average increase of 8000 active aircraft per year. This projected yearly increase will be composed of 6000 single-engine, piston-powered aircraft, 1200 multi-engine, piston-powered aircraft, and 800 turbine-powered aircraft - the latter category including both fixed and rotary-wing (helicopter) aircraft.

The distribution of active civil aircraft by year of manufacture is presented in Table 5 for aircraft manufactured during 1966 and earlier. From this Table, it is observed that the median age of these aircraft is approximately 8 years. That is, approximately 50 per cent of the active civil aircraft in the United States are over 8 years old.

The distribution of all registered civil aircraft by type of registrant, as of March 31, 1968, was as follows:

Individual	93,008
Corporation	54,848
Coowner	9,801
Partnership	7,912
Government	2,790

This list was determined by the FAA from an analysis of aircraft registration data (Ref 15).

Civil aircraft operations are generally classified into two broad categories: air carriers and general aviation. The distributions of aircraft types in these categories are described in the following sections.

Air Carrier Aircraft

Air carrier aircraft are a category of civil aircraft which are used for the transportation of persons or property for hire. These aircraft are operated by certificated route air carriers, supplemental air carriers, and commercial operators. Approximately 90 per cent of the aircraft in this category are operated by the certificated route air carriers, or "scheduled airlines". Supplemental air carriers are authorized to perform passenger and cargo charter service and scheduled operations on a limited or temporary basis. Commercial operators are authorized to transport passengers or cargo on a private for-hire basis. Air taxi operators are not included in the air carrier category, but are included under General Aviation.

The composition of the United States Air Carrier fleet is described in Table 6 as reported by the FAA for recent years and projected for future years. A more detailed description of the air carrier fleet, as of January, 1968, is presented in Table 7. The total number of aircraft in the fleet (approximately 2500) is a small fraction of the total United States aircraft population (2 per cent). However, air carrier aircraft are responsible for a highly disproportionate share of total aircraft activity. Since air pollutant emission is more directly related to activity than population, air carriers constitute a category of aircraft of particular importance to this study.

The changing size and composition of the air carrier fleet is shown in Figure 4. The projected rate of growth of the fleet, 50 per cent increase over the next 10 years, is somewhat less than the corresponding projection for all civil aircraft (70 per cent). However, a more striking change is the rapid conversion of the fleet to turbine-powered aircraft. Piston-powered aircraft constituted nearly 90 per cent of the total in 1960, but make up only 15 per cent today, and this percentage will continue to diminish. Within the turbine-powered category, aircraft fitted with turbofan engines will be responsible for the over-all growth of the air carrier fleet. Turbojet and turboprop aircraft are expected to remain essentially constant in number in the near future.

Aircraft built by foreign manufacturers are of interest from the standpoint of emission control in that control methods cannot always be applied to these as readily as with aircraft built in the United States. Aircraft operated by air carriers which were built in foreign countries are listed by type in Table 8. Foreign-made aircraft constitute approximately 7 per cent of the total fleet, and this fraction consists almost entirely of turbine-powered, fixed-wing aircraft. As stated above, future growth of the air carrier fleet will consist largely of turbofan-powered aircraft. At the present time, foreign-made aircraft constitute approximately 10 per cent of this category, and these aircraft were built by two manufacturers, the British Aircraft Corporation (BAC 111) and Avions Marcel Dassault (Fan Jet Falcon). However, of 940 fanjets on order by the air carriers on May 15, 1968 (Ref 21), only 7 will be purchased from a foreign manufacturer (BAC). Consequently, the foreign-built segment of the air carrier fleet is expected to decrease, both numerically and in percentage, during the next five years. This trend may change slightly with the introduction of the supersonic Concorde, but the future of this aircraft is uncertain at present.

General Aviation Aircraft

General aviation is a broad category including all civil aircraft except those of the air carriers. This category includes aircraft used in the following types of flying, as defined by the FAA:

1. Business
    - (a) Executive transportation (professional pilot)
    - (b) Business transportation (owner-piloted)
2. Personal
3. Instructional
4. Commerical
    - (a) Air taxi
    - (b) Aerial application (agricultural spraying, etc.)
    - (c) Industrial/special (photography, advertising, etc.)
5. Other

The "other" category includes aircraft operated by federal, state, and local government agencies.

Numbers of various types of active general aviation aircraft are listed in Table 9 for recent years, and as projected by FAA for future years. A more detailed description of general aviation aircraft, as of January, 1967, is presented in Table 10. Population growth rates are indicated in Figure 5. The growth rate of the GA aircraft population increased abruptly in 1965 and currently is about 8000 aircraft per year. This rate is expected to continue into the foreseeable future.

The air taxi fleet is an element of the general aviation fleet which is growing rapidly and is responsible for a significant fraction of GA activity, particularly at air commerce airports. As of October 1967, the fleet of the scheduled air taxi operators consisted of the following aircraft (Ref 22):

Fixed-Wing	
Single-engine piston	200
Multiengine piston	452
Turbine	24
Helicopter	9
Total Aircraft	685

Most air taxi operators are located around traffic hubs and serve as feeders and extensions to the air carriers.

In contrast to the air carrier fleet, general aviation aircraft are powered mainly by piston engines. Turbine-powered GA aircraft constitute about 1 per cent of the total population today, and this fraction is expected to increase to 3 per cent in 1979. Single-engine, piston-powered aircraft, which are popular for personal, instructional, and small-business flying, dominate the population figures.

The fraction of United States general aviation aircraft built by foreign manufacturers is very small, probably less than 1 per cent of the total number of active aircraft. In certain categories, however, the fraction is higher. From 5 to 10 per cent of aircraft used for air taxi service and turbine-powered, business aircraft are built by foreign manufacturers.

Military Aircraft Population

The aircraft inventory of the United States Department of Defense, as of December 31, 1967, consisted of 33,749 aircraft. Their distribution among the services is shown in Table 11. Information on the distribution of aircraft types is not available. However, engine production figures indicate that the military inventory is powered mainly by turbine engines.

Aircraft Engine Population

Aircraft engines of principal interest in this report are those installed in aircraft active in the United States. Other engines of lesser interest are those installed in inactive aircraft and engines held in inventory for new or replacement installation. The latter category does not include a significant number of engines as most aircraft engines are built on order for installation in aircraft under production. Also, engine replacement in civil aircraft is required only infrequently. Engines are subject to regular overhaul and parts replacement, but most engines retain their original identity and last the life of the aircraft in which they are installed. Turbine engines in use in the United States air carrier fleet are listed in Table 12, and piston engines are listed in Table 13. Corresponding population data on general aviation aircraft engines could be obtained by analysis of FAA aircraft registration data.

Aircraft and Aircraft Engine Production

Aircraft Production

Numbers of aircraft produced in the United States during recent years and projections for future years are listed in Table 14. The fraction of civil aircraft which are exported is between 15 and 20 per cent currently. The major manufacturers of civil aircraft in the United States are listed in Table 15. These figures include all domestic production of transport aircraft, commercial helicopters, and nearly all general aviation aircraft. Not included are small manufacturers and individuals who account for a small fraction of the production of general aviation aircraft. Foreign manufacturers of aircraft sold to United States parties are listed in Table 16.

Aircraft Engine Production

Numbers of aircraft engines produced in the United States during recent years and projections for future years are listed in Table 17. As in the case of aircraft, 15 to 20 per cent of United States-produced, civil aircraft engines are exported.

United States manufacturers of civil aircraft engines are listed in Table 18. Compared to aircraft manufacturers, the number of engine manufacturers is small. Two manufacturers supply nearly all aircraft piston engines, and two others supply most aircraft turbine engines. However, other turbine engine manufacturers, notably Allison and Garrett, are increasing their sales of engines for civil aircraft.

Aircraft engines produced by foreign manufacturers are imported either installed in foreign-made aircraft, or separately for installation in United States-made aircraft. Installed engines are listed in Table 16, and separate engines are listed in Table 19. At the present time, most engines imported into the United States, either installed or separate, are turbine engines and all are produced by three manufacturers: Rolls-Royce, Limited, of the United Kingdom, Société Turbomeca of France, and United Aircraft of Canada, Limited.

In contrast with the automobile industry, nearly all manufacturers of aircraft engines are independent from aircraft manufacturers. Also, the number of engine manufacturers is small compared to the number of aircraft manufacturers. Because of these factors, governmental control of pollutant emission by aircraft, if required, could be applied more conveniently to aircraft engines than to aircraft.

Aircraft Activity

A variety of measures can be used to describe aircraft activity, e.g., landings, take-offs, hours flown, passengers carried, etc. From the standpoint of engine emissions and their local and community effects, the most significant activity is that which occurs in the air terminal vicinity. In this report, the "landing-take-off (LTO) cycle", as defined earlier, has been adopted to characterize the operation of an aircraft between the time it begins its approach to a terminal for landing and the time it subsequently leaves the terminal area after take-off. In this section, LTO-cycle frequency is used as a measure of aircraft activity. In later chapters, the LTO-cycle concept is utilized to assess aircraft emissions and their impact.

Data presented on aircraft activity in this section have been taken from various FAA publications which describe activity at air terminals with FAA-operated air traffic control towers and at military installations. Activity at non-FAA-controlled, civil air terminals is not included except for Los Angeles County. However, most terminals within other major metropolitan areas are controlled either by the FAA or by one of the military services. Thus, most of the activity affecting community air pollution is included.

Aircraft Activity at All Major U. S. Air Terminals

The numbers of LTO cycles occurring annually within the United States, as reported by the FAA, are listed in Table 20 for recent years. Projections of civil aircraft activity for future years also are listed. These numbers are shown graphically in Figure 6. These activity figures are for FAA-controlled air terminals of which there were 913 in 1967 compared to a total of 9673 civil airports in the United States. Consequently, a substantial amount of general aviation activity is not included in these figures. However, most of this activity occurs outside of urban areas and, consequently, has little impact on urban air pollution.

The two primary observations which can be made from these numbers is that nationwide aircraft activity is increasing at a rapid rate (approximately 10 per cent per year), and that general aviation aircraft account for the bulk of this activity. However, the distribution of activity by aircraft category as shown is not typical of individual air terminals or communities. Most military activity occurs at installations removed from major metropolitan areas, and civil air terminals vary widely as to the ratio of air carrier to general aviation activity.

Aircraft owned by foreign organizations or individuals and operated in the United States are a special activity category. These aircraft probably would not be subject to emission controls established by pollution control agencies in the United States. Consequently, the fraction of U. S. aircraft activity represented by foreign-owned aircraft is of interest to this study. Air carriers are the only aircraft category with a significant amount of activity by foreign-owned aircraft. According to an analysis of flight schedules (Ref 31), the fraction of air carrier activity (LTO-cycles) conducted by foreign aircraft rose from 2 per cent in 1965 to approximately 6 per cent in 1967 (excluding special flights by Air Canada serving Expo 67). During this same period, the number of foreign air carriers operating at United States air terminals increased from 24 to 49. For comparison, there are 17 United States carriers engaged in international operations and these account for 2 to 3 per cent of total activity at United States terminals. Thus, it is observed that, on a national basis, foreign-owned aircraft account for a small, but growing fraction of air carrier activity. This fraction will be greatest at the international air terminals, such as John F. Kennedy.

Average Aircraft Activity at Selected Major Air Terminals

The number of aircraft LTO-cycles performed during 1967 at major air terminals in the New York City, Washington, D. C., and Los Angeles metropolitan areas are listed in Tables 21, 22, and 23. It is observed from these tables that the distribution of aircraft activities among the major categories in these areas differs from the national distribution, the principal difference being in the air carrier category. The statistics for the New York City area depart the most from the national average in that 40 per cent of all LTO-cycles were performed by air carriers.

In examining activities at individual air terminals, it is observed that nearly all terminals can be characterized by a single aircraft category, that is, terminal activities are predominately air carrier, general aviation, or military. The only exception in the areas examined is Dulles International which, in 1967, had a rather even distribution of activity in the three categories.

Of particular interest to this study is the distribution of aircraft activity by aircraft type. Records of certificated route air carrier activity by type of aircraft are published jointly by the CAB and FAA (Ref 32). These records were used to determine the distribution of air carrier activity during calendar year 1967 by aircraft class. Commercial operator, supplemental, and foreign air carrier activity, not included in these records, was assumed to consist of one-third class 1 aircraft and two-thirds class 2 aircraft.

No records are kept of general aviation activity by aircraft type. For this study, all GA activity has been assumed to consist of class 6 aircraft.

Similarly, no information has been obtained on military activity by aircraft type. An estimate of the distribution of military aircraft types was made based upon various compilations of aircraft currently in service (Refs 19 and 33). The estimated distribution of military activity is as follows:

Class 3 aircraft	50 per cent
Class 4 aircraft	15 per cent
Class 5 aircraft	10 per cent
Class 6 aircraft	20 per cent
Class 7 aircraft	5 per cent

In preparing this distribution, it was assumed that strategic bomber aircraft, which might be considered to fall into class 1, do not operate from terminals within the metropolitan areas included in this study. Attack and fighter aircraft are typified by the class 3 category, at least in terms of performance. The fuel consumption rates of these aircraft are considerably greater than those of civil, class 3 aircraft. This difference has been taken into account in calculating fuel consumption and pollutant emission at air terminals.

Using the approaches outlined in the preceding paragraphs, estimates of daily activity by aircraft class have been made for five air terminals, three metropolitan areas, and for all FAA-controlled terminals combined. These activity levels are listed in Table 24.

Timewise Variations of Aircraft Activity

Variations in activity levels from average levels at civil airports are published occasionally by the FAA, the most recent data being for fiscal year 1965 (Ref 34). Using these data and assuming that the same peak-to-average ratios existed in 1967, peak daily and hourly activity rates were calculated for each of the civil air terminals listed in Tables 21, 22 and 23, and these rates are listed in Tables 25, 26 and 27. The times at which these peak rates occur are not reported. However, timewise variation in activity rates for air carrier operations have been reported (Ref 31). The daily rate (nationwide) of air carrier activity reaches a peak on Friday. Activity levels are less by about 1 per cent on Monday through Thursday and by 17 and 15 per cent on Saturday and Sunday, respectively. Hourly levels of scheduled air carrier and air taxi activity for five municipal areas are shown in Figure 7. In general, the activity rates are high from 10 am to 10 pm and lower during the other half of the day. Activity peaks occur in the morning and the early evening, and the lowest activity level occurs around 4 am.

Current activity levels at John F. Kennedy, Washington National, and Los Angeles air terminals are listed in Tables 28, 29 and 30 by hour of arrival and type of aircraft. These figures are for scheduled activity and were taken from References 35 and 36. Passenger and cargo air carrier activities and air taxi activities are included. Some intrastate operations are not included, but these represent a small fraction of the total. The number of scheduled flights actually flown is typically about 95 per cent of those scheduled.

The timewise variations of activity levels at general aviation and military air terminals are not published. However, it is reasonable to assume that most operations occur during daylight hours.

Summary

This section is a compilation of statistical data on aircraft population, production, and activity which have been used in this study in determining rates of pollutant emission and evaluating emission control methods. In compiling this information, the following general observations have been made:

1. The Federal Aviation Administration classifies civil aircraft into two broad categories: air carriers and general aviation. Air carrier aircraft consist mainly of turbine-engine transport aircraft. General aviation aircraft consist mainly of medium and small-size, piston-engine aircraft.
2. The population of active, civil aircraft is approximately 100,000 and is increasing at the rate of about 8000 aircraft per year. Air carrier aircraft constitute about 2 per cent of the total population.

3. The number of aircraft engine manufacturers in the United States is small (approximately 8) compared to the number of aircraft manufacturers. Also, engine manufacturers are largely independent from aircraft manufacturers.
4. Activity at most air terminals is dominated by one of three classes of aircraft: air carrier, general aviation, or military. Activity at major metropolitan terminals consists mostly of air carrier and air taxi activity.
5. Civil aircraft activity levels, as measured by frequency of landing and take-off operations, are increasing at a rate of approximately 10 per cent per year. General aviation activity levels are increasing at the greatest rate.

These observations are pertinent to the problems of pollutant emission by aircraft and its control. Their implications are brought out in later sections of this report.

AIRCRAFT FUELS

The rates of emission of pollutants by most internal combustion systems, including aircraft engines, are determined partly by the nature of their fuels and their rates of fuel consumption. Thus, a knowledge of fuel characteristics and consumption rates can be used to estimate the rate of pollutant emission by a particular source. This approach is particularly useful in the case of aircraft engines since fuel consumption data for these engines are readily available.

In this section, characteristics of aircraft fuels are described, and data on fuel consumption are presented for individual aircraft engines. These data have been used with aircraft activity data from the previous section to determine over-all rates of consumption of aircraft fuels at air terminals and in metropolitan areas. In the following section, these consumption data are used, along with data on engine exhaust characteristics, to determine rates of pollutant emission.

Fuel Characteristics

Fuels currently used in aircraft engines consist of mixtures of hydrocarbons produced by the distillation and post-processing of crude oil. The products of a typical refining operation and the relative quantities produced by atmospheric distillation are shown in Figure 8. Aviation fuels are taken from the gasoline and kerosine fractions, and consist of many organic compounds with boiling points within the range of 140 to 550 deg F. A typical gasoline contains as many as 240 chemical compounds (Ref 37) and JP-4, a military jet fuel, may contain as many as 5000 to 10,000 different compounds.

Specifications on properties of aircraft fuels are based upon several factors, including engine requirements, storage stability, airframe requirements (minimization of fuel tank size, limitation of evaporative losses, and prevention of autoignition in high speed aircraft), and, one that is becoming of increasing importance, availability. The kerosine fraction from crude oil has to meet requirements of other users besides aircraft and it is clear from Figure 8 that the fraction available is only about 10 per cent of each unit of crude oil processed. With the demand for turbine-engine fuels increasing rapidly, a shortage of kerosine could develop. Such a shortage could be overcome by various means, including chemical conversion of other less useful fractions of crude oil (at an increase in cost of the fuel), modification of fuel specifications, or importation of kerosine from other countries. The last two solutions are currently employed. Specifications for military fuels allow a greater fraction to be used, equal to approximately 40 per cent of the crude oil, thus avoiding any shortage for military use in time of emergency. Also, jet fuel is imported in significant quantities. For example, 16 per cent of the total U. S. consumption of jet fuel in 1966 was imported (Ref 38). The present trend in refining, however, is toward chemical processing (hydrocracking) in order to produce additional kerosine and gasoline type fuels from the heavier gas oils (Ref 39).

Fuel specifications are usually defined in terms of limits on certain physical properties, and fuels of significantly different chemical composition can satisfy the same physical property requirements. It is also necessary to specify composition limits of certain undesirable chemical groups. For example, aromatic compounds such as naphthalenes are undesirable as they have a strong tendency to produce smoke during combustion.

The basic chemical nature of a fuel depends mainly upon the source of the crude oil from which it is derived since important differences exist in crude oils. Figure 9 shows the variation in one physical property, namely, the tendency to smoke, of the kerosine fractions produced from different oil sources. The effect of removing all aromatics from the kerosine is also indicated. South American crude oils are shown to be the least desirable from this particular aspect as, even after the expensive step of aromatic removal, they produce kerosine fractions which are as prone to smoking as the untreated kerosine derived from African and Middle East crude oils. Crude source, therefore, is also an indirect factor influencing fuel specifications which are usually written primarily to ensure delivery of a satisfactory fuel at as low a cost as possible.

Piston-Engine Fuels

Fuels used in aircraft piston engines are similar to automobile fuels and are referred to as aviation gasolines, often abbreviated as AVGAS. They are classified according to a combustion characteristic termed antiknock quality. The fuel-air mixture in the cylinder of a piston engine will detonate under certain conditions instead of burning normally. Detonation or knock is usually inaudible in an aircraft engine, but if permitted to continue, can result in serious loss of power and damage to the engine. The antiknock value, or octane rating, of a fuel indicates its ability to prevent such an occurrence, higher octane values being more desirable. Specifications for aviation gasolines define five grades with different octane ratings but only two are commonly available with ratings of 100/135 and 115/145. The two values in each rating are lean and rich ratings corresponding to full-lean and full-rich mixture control settings. (See Aircraft Fuel Systems.)

Aviation gasolines are mainly complex mixtures of relatively volatile hydrocarbons. They contain some impurities, such as sulfur compounds, which originate in the crude oil. In addition, certain materials are added to improve quality of performance. The most important additive is tetraethyllead which is added to increase the octane rating of the fuel. It is added as a fluid together with an organic halide scavenging agent which is necessary to keep the tetraethyllead combustion products volatile so that they will be discharged from the cylinder. Antioxidants are also added in small quantities to inhibit the formation of insoluble gums during storage of the fuel.

Aviation fuels cannot be defined precisely due to their complex chemical composition. Fuel specifications, therefore, are stated in terms of limits on physical and sometimes chemical properties of the desired fuel. The limits are prepared from a consideration of those factors that significantly affect aircraft operation together with others such as cost and availability of the fuel. The most significant factors are listed below together with the standard test methods which are used to assign quantitative values to these properties of interest (Ref 41). Detailed specifications for all five grades of aviation gasoline are given in Table 31.

IMPORTANT CHARACTERISTICS OF AVIATION GASOLINE

Factors of Significance	Test Methods
Antiknock quality	Knock test Tetraethyllead analysis
Fuel metering and aircraft range:	Net heat of combustion
Carburetion and fuel vaporization:	Vapor pressure Distillation
Corrosion of fuel system and engine parts:	Acidity of distillation residue Copper strip test Sulfur analysis
Fluidity at low temperatures:	Freezing point
Fuel cleanliness, handling and storage stability:	Water tolerance Potential gum Visible lead precipitate

Turbine-Engine Fuels

Turbine-engine fuels are not classified in terms of engine performance factors. The engine itself is not as sensitive to fuel properties as the piston engine, but other factors are more significant. For example, airframe requirements are more demanding due to the higher altitudes and speeds at which turbine-powered aircraft operate. Also, the relative availability of the kerosine fraction favored for these engines is far more limited than the availability of gasoline. On the basis of these factors, turbine-engine fuels can be separated into four main types: fuels for civil aircraft, for the Air Force, for the Navy, and for experimental aircraft.

The two fuels most commonly used in civil aircraft are taken directly from the kerosine fraction and are referred to as Jet A or Avtur 40 and Jet A1 or Avtur 50. The Avtur number indicates the freezing point of the fuel in degrees centigrade (below zero). Jet A1 or Avtur 50 for example has a freezing point lower than -50 deg C. This was the fuel first used in jet engines, but due to its limited supply, the alternative fuel, Jet A, is now in more common use. Its 10 degree higher freezing point allows refinery blending of Jet A1 with heavier fuels which are in less demand, and hence more turbine fuel is obtained per unit of crude oil.

To satisfy availability requirements in time of emergency, the Air Force operates on a different fuel known as JP-4. (Jet B, wide-cut and Avtag also are used to describe this fuel). The specifications for JP-4 allow nearly 40 per cent of the crude oil to be converted into usable fuel. JP-4 contains a higher concentration of light hydrocarbons than other turbine engine fuels, and, as a result, is appreciably more volatile and ignites more readily than the Jet A and Al fuels. It is claimed by some to be unsafe for commercial use because of its volatility (Ref 42).

The fuel used by the Navy was developed for aircraft carrier use and is called JP-5. It is less volatile than even Jet A and ignites less readily.

The fourth fuel category includes fuels used in experimental aircraft. Military specifications have been prepared or proposed for several such fuels including JP-6 and JP-150. They are intended for use in high-speed, supersonic aircraft, and this application calls for fuels with low volatility and high thermal stability.

Most turbine-engine fuels--Jet A, Jet Al, JP-4, JP-5 and JP-6--are specified mainly by their physical properties, but their chemical compositions vary with crude oil and refinery sources. JP-150 fuel, however, is specially refined to consist mainly of paraffins. Some indications of the approximate composition by chemical groups of all turbine engine fuels are given in Table 32. Appreciable variations in composition do exist for fuels satisfying the same specifications (Ref 45).

As with aviation gasolines, turbine-engine fuels contain impurities derived from the crude source and other substances which are added to improve fuel performance. Sulfur is present as an impurity with a concentration level of approximately 0.05 mass per cent. The main compound added to these fuels is an antioxidant which prevents the formation of insoluble gums during storage. The quantity added is approximately 0.002 mass per cent. Experimental attempts have been made in recent years to reduce jet engine exhaust smoke with fuel additives and successful results have been obtained using metal-organic compounds of barium, manganese, and iron (Ref 96). Concentration levels of 0.1 per cent were observed to be effective when used with JP-5 fuels. However, detailed study of the effects of additives has shown that engine performance deteriorates rapidly when such additives are used as a result of deposition of particulate matter upon the combustor and turbine parts. This effect, coupled with possible toxicity problems, makes it very unlikely that the use of additives for smoke reduction will ever be widely accepted.

Desirable characteristics of turbine-engine fuels are listed below with the physical or chemical property normally measured to compare the effectiveness of different fuels (Ref 49).

Factors of Significance	Requirements
Combustion Characteristics:	
Fuel Vaporization	Volatile Distillation Properties
Flame Cleanliness	High Luminometer Number
Fuel Metering and Aircraft Range:	Value of Net Heat of Combustion
Airframe Considerations:	
Fuel Fluidity at Low Temperatures	Low Freezing Point
Fuel Tank Size	High Specific Gravity
Fuel Cooling Capability	High Specific Heat
Evaporative Losses	Low Vapor Pressure
Autoignition	High Flash Point
Corrosion of Fuel System:	Low Acidity Low Sulfur Content
Fuel Cleanliness, Handling, and Storage Capability:	High Water Tolerance Low Existent Gum Low Potential Gum Good Fuel Lubricity Low Viscosity High Thermal Stability

Characteristics of kerosine which were of little interest before the advent of the turbine engine include flash point, thermal stability, specific heat, fuel lubricity and the luminometer number of the fuel. Luminometer number is an empirical factor which provides some indication of the cleanliness of the flame produced in the combustor, and a value greater than 45 is usually required to achieve satisfactory combustor performance (Ref 47). Fuels with lower values tend to produce excessive smoke even when used in well-designed combustors. The smoke gives rise to carbon deposition and reduces combustor life due to the higher radiant heat transfer from the flame. The luminometer number is related to the chemical composition of the fuel and its hydrogen-to-carbon ratio. Saturated hydrocarbons (paraffins), with their high H/C ratio, produce less smoke than relatively low H/C ratio unsaturated compounds such as olefins and aromatics. The other factors listed above became of increasing importance as flight velocity increases.

Most of the fuel properties of interest are interdependent and often it is necessary to compromise between various factors. It is not possible, for example, using hydrocarbons alone, to obtain both a low vapor pressure and the high heat content per unit volume desired by the airframe designer, and at the same time maintain a high luminometer number required for the combustor. Thus, there are limits in operating conditions under which current fuels can operate. Fuels such as Jet A are satisfactory for aircraft with flight velocities up to about Mach 2.7. The Boeing SST will use Jet A and operate at Mach 2.7. However, above this speed, airframe requirements cannot be met without resorting to a more highly refined fuel such as JP-6.

There are more specifications for aviation turbine fuels than there are fuels available. They are prepared by engine manufacturers, military authorities, commercial aircraft operators, the American Society for Testing and Materials, and other groups. Fuel producers meet the various requirements by blending fractions which satisfy more than one specification. Consequently, there are available only the four main types of fuel described earlier.

Normally a turbine engine fuel specification will limit the value of approximately thirty physical or chemical characteristics resulting in overspecification due to the interdependence of the properties. It has been shown, for example (Ref 48), that five main properties specified for the kerosine fuels Jet A and Jet A1 can be determined from the experimental measurement of only two of these properties. The other three properties can be calculated with an accuracy better than that associated with one experimental determination. Typical specifications for aircraft turbine-engine fuels are shown in Table 33.

Fuels for the Future

Present activity in aviation fuels research is mainly involved with the development of economical, hydrocarbon fuels for supersonic aircraft (Ref 50 and 51). Other activities include the production of emulsified JP-4 fuels (Ref 52) with the objective of reducing the fire hazard in aircraft accidents, and studies of the feasibility of obtaining fuels from sources other than crude oil. The latter program has two objectives; firstly, to produce fuels with high volumetric heat content for advanced air breathing systems, and secondly, to study the possibilities of using liquefied methane (natural gas) or hydrogen in supersonic aircraft.

Attention is turning to nonpetroleum based fuels because of the operational difficulties that arise in supersonic flight. At high velocities, air flowing over the aircraft is heated by compression and skin friction and cannot be used for cooling purposes. Instead, stored fuel is used for cooling auxiliary systems, such as air-conditioning, hydraulic fluid, and engine lubrication systems. At high supersonic velocities, it may also be necessary to utilize fuel for cooling certain portions of the aircraft structure. In this case, fuels will be required having greater cooling capacity than those in current use (Ref 53). Liquefied methane and hydrogen have large cooling capacities, but problems associated with their low densities and low boiling temperatures offset their advantages as coolants. It is most likely, therefore, that hydrocarbon fuels, with some modifications, will be used for all aircraft propulsion for many years.

Fuel Consumption

The rate of emission of air pollutants by an aircraft engine, as with other internal combustion engines, is highly correlated with its fuel consumption rate. Other factors affect pollutant emission rates, of course, but engines of the same type operating at similar conditions will emit pollutants at rates directly proportional to their fuel consumption rates. Consequently, fuel consumption statistics are relevant to this study.

Consumption of fuel by U. S. aircraft in recent years is shown in Table 34 and in Figure 10 along with projections for future years. The decreasing trend of aviation gasoline consumption is a result of the retirement of piston-engine transport aircraft. Air carrier aircraft, though constituting only 2 per cent of the U. S. civil aircraft population, consume approximately 90 per cent of all aircraft fuel used in civil aviation. Daily fuel consumption by aviation category, is as follows:

Daily Fuel Consumption by U. S. Civil Aircraft
(Thousands of Pounds - Average Day, 1967)

	Aviation Gasoline	Turbine Fuels	Total
Air Carriers	5,500	74,000	79,500
General Aviation	6,000	2,100	8,100
All Civil Aircraft	11,500	76,100	87,600

In comparison with fuel consumption by aircraft, daily consumption rates of automobile gasoline in the United States is approximately 1,200,000,000 pounds (Ref 54).

Air carriers dominate the fuel consumption statistics because the size and engine power levels of air carrier aircraft are so much greater than those of most general aviation aircraft. This size disparity is reflected in a comparison of fuel consumption rates for different engine types as indicated in Table 35 and quantities of fuel consumed during landing-take-off cycles shown in Table 36. The LTO-cycle fuel consumption estimates are based upon the cycle characteristics listed in Table 2 and the fuel rates listed in Table 35. It is observed from these estimates that general aviation aircraft, which are mostly class 6 aircraft, individually consume very small quantities of fuel compared to air carrier transport aircraft (classes 1, 2, 4 and 5).

By combining the fuel consumption data from Table 36 with the aircraft activity levels presented earlier, average daily fuel consumption rates at air terminals have been calculated and are presented in Table 37.

This table shows daily fuel consumption rates for all aircraft operating from certain air terminals and communities.

Based on the data presented, it is estimated that 20 to 25 per cent of all fuel consumed by U. S. civil aircraft is consumed during operations at air terminals.

Summary

In this section, we have shown that fuels used in aircraft engines are similar to fuels used for other purposes. Aircraft piston engines use aviation gasoline which is similar to automobile gasoline and, like most automobile gasoline, contains tetraethyllead to prevent engine knock. Turbine engines in civil aircraft use aviation kerosine which is similar, in many respects, to fuels used in automotive diesel engines. Aviation kerosine, however, is subject to more stringent limitations on impurity levels and smoke-forming tendencies than most other fuel oils.

The fuel consumption rates of transport aircraft are large compared to those of general aviation aircraft, and the consumption of turbine-engine fuels by civil aircraft greatly exceeds that of piston-engine fuels (aviation gasoline). Between 20 and 25 per cent of all aviation fuel used by civil aircraft is consumed during air terminal operations.

This information on fuel characteristics and consumption rates is used in the next section to estimate rates of pollutant emission by aircraft during air terminal operations.

AIRCRAFT ENGINE EMISSIONS

The purposes of this section are to describe the nature of aircraft engine exhaust emissions, and to indicate the quantities of air pollutants emitted during aircraft operations. In the first part of the section, pollutant species contained in engine exhaust gases are described, and other characteristics of exhaust gases--visual appearance and odor--are discussed. Methods of measuring concentrations of pollutants and exhaust gas characteristics are described in Appendix I.

In subsequent parts of this section, the mechanisms of pollutant formation and the rates of pollutant emission by individual engines are discussed. Effects of engine design and operating characteristics on emission rates are presented, to the extent that they are known. This information is used to estimate the rates of emission of various pollutants by different engine types during various operational modes (take-off, approach, taxi, etc.).

Finally, estimates of the daily rates of pollutant emission at air terminals are presented. These estimates are based upon individual engine emission rates presented in this section, and data on aircraft activity and fuel consumption presented in earlier sections. Estimates of pollutant emission during all aircraft operations are presented. However, greater emphasis is given to emissions at specific air terminals and in selected urban areas.

Characteristics of Aircraft Engine Exhaust Gases

Composition

The gross composition of exhaust products from typical aircraft engines is presented in Table 38. Exhaust gases from both piston and turbine engines consist mainly of substances which are not regarded as air pollutants--nitrogen, oxygen, and water. Pollutant materials are present in lesser quantities and can be categorized as follows:

(1) carbon dioxide
(2) carbon monoxide
(3) organics
(4) nitrogen oxides
(5) particulates
(6) sulfur dioxide

It is observed that concentrations of these materials are substantially different in the two engine types and that they also vary with engine operating conditions. Pollutant concentrations and rates of emission are discussed more fully later in this section.

Chemical and Physical Properties

Properties of pollutants are described briefly here with particular emphasis on those characteristics which are peculiar to aircraft engine exhaust emissions. A variety of references are available which provide more extensive descriptions of properties of pollutants and their effects (e.g. Ref 57).

Carbon Dioxide

Carbon dioxide is a colorless, ordorless gas and is a normal constituent of exhaust gases from all combustion systems which burn carbonaceous or hydrocarbon fuels, natural fuels such as wood, and most waste materials. Since the beginning of the twentieth century, world-wide atmospheric concentrations of carbon dioxide have been increasing steadily in a manner related to the increased global use of fossil fuels (Ref 58). Carbon dioxide is not often considered to be an air pollutant, since it produces adverse physiological effects only at relatively high concentrations and because biological and geochemical processes are known to provide a natural disposal system. Its atmospheric increase apparently reflects an accelerating disparity between the CO_2 production rate and the rate of approach to equilibrium with marine and terrestrial sinks. Unchecked increase in the rate of combustion of carbon fuels apparently may increase world-wide CO_2 levels eventually to meteorologically significant levels. However, since CO_2 is not regarded as a pollutant from the standpoint of community air quality, it has not been included in this study.

Carbon Monoxide

Carbon monoxide is of interest as an air contaminant primarily because of its toxic properties. The highest outdoor levels of carbon monoxide are often found where vehicular traffic is heaviest. Indicative of the increasing urban impact of carbon monoxide is the fact that in the fall of 1964 during unusually long and severe inversion conditions, carbon monoxide was monitored in quantities as high as 20 parts per million (ppm) for eight hours, and higher concentrations (up to 72 ppm) have been reported for shorter periods of time (Ref 57). The threshold limit value of CO

(TLV), as adopted by the American Conference of Governmental Hygienists in May 1967, is 50 ppm. The TLV refers to the airborne concentration of a substance to which a worker may be exposed for an eight-hour day, five days a week without adverse effect. The problems which arise in the ambient situation, however, are that exposed individuals are not necessarily workers (e.g. children, elderly people, etc.), are not reimbursed for their exposure, and may be exposed for periods longer than eight hours.

CO is also a colorless, odorless gas and is chemically stable. It is oxidized to CO_2 in the atmosphere, but at very slow rates.

Organics

Organics is a term used to describe substances consisting mainly of carbon and hydrogen with lesser quantities of oxygen and nitrogen. These materials also are referred to as "hydrocarbons", but there are a number of pollutant species of an organic nature which are not truly hydrocarbons. Organics, as used in this report, include pollutant species in both gaseous and liquid state.

Most organic materials are not directly harmful at low concentrations, but are converted to harmful materials through photochemical reactions. The reaction which represents this phenomena is HC+NO +sunlight→smog. Haagen-Smit has shown that ozone is also formed during the photochemical oxidation of organics in the presence of nitrogen dioxides (Ref 57). If one were to attempt to catalog organic compounds which have been observed or might be expected to be detectable in contaminated air, the list would be a very extensive one. That the chemical composition of organic air contamination is complex is emphasized by noting some possible reasons for presence of gas phase organics in the atmosphere. Leakage

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Most methods used to measure hydrocarbon emissions from aircraft engines also respond to non-hydrocarbon, organic compounds. The term organics has been used throughout this report to describe this pollutant category.

or loss of any gas or liquid fuel, solvent, etc. would be a direct source of many organic species. Both incomplete oxidation and cracking of fuels in combustion processes can lead to another group of compounds. To these primary sources we need only add the known fact of photochemistry in the atmosphere, which produces both unknown free radicals and also organic peroxides, peracids, hydroxyperacids and such nitrogen-containing compounds such as peroxyacetyl nitrates. With this variety of sources it seems reasonable to estimate that with refinement of observation techniques, many hundreds of individual organic chemicals could be isolated from the atmosphere. The primary adverse effects of these compounds are physiological effects on man or animals, material damage, agricultural damage, and visibility reduction.

Among the more important oxygen-containing organics are the aldehydes which have been identified repeatedly and which are of interest in air pollution because of their effect on humans. At low concentrations, several of them are very irritating to the eyes and to mucous membranes. Since the photochemical oxidation of unsaturated olefinic hydrocarbons results in the formation of formaldehyde, ocrolein, acetaldehyde, propionaldehyde and isobutylaldehyde, these should be present in polluted air. Of these, formaldehyde appears to be the most prevalent. The aldehyde content of air in several United States cities between the years 1946 and 1951 ranged from 0.00 to 0.27 ppm. In that period the average concentration varied from 0.04 to 0.18 ppm calculated as formaldehyde. The reported high concentration of aldehydes in Los Angeles through 1959 was 1.87 ppm with the usual range being 0.01 to 0.20 ppm with a mean concentration of 0.04 ppm (Ref 57). (TLV= 5.0 ppm)

Organic compounds in exhaust products from aircraft engines include unburned components of the fuel and organic substances formed during combustion. A partial listing of organics contained in exhaust gases from an aircraft turbine engine is presented in Table 39.

Nitrogen Oxides

Of the six commonly encountered oxides of nitrogen - N_2O (nitrous oxide), NO (nitric oxide), NO_2 (nitrogen dioxide), N_2O_3 (nitrogen trioxide), N_2O_4 (nitrogen tetroxide), and N_2O_5 (nitrogen pentoxide) - NO_2 is considered of the greatest air pollution interest for three reasons: (1) Most other oxides of nitrogen react in air in such a way that the principal product is NO_2. (2) NO_2 is believed to be one of the chief substances in the chain of ultraviolet reactions with atmospheric hydrocarbons that leads to oxidant smog. (3) Nitrogen dioxide results as a major end product of the burning of fuel in engines and furnaces because of air oxidation of the NO formed by high combustion temperatures. Because of the low relative toxicity and air pollution significance of N_2O and N_2O_3 and N_2O_4, only the properties of NO_2, NO and N_2O_5 will be discussed.

Although particulate matter is the most important factor in determining the loss of visibility in polluted atmospheres, there has also been considerable interest in sky color effects, especially the brown discoloration which occurs as a result of excessive NO_2 concentrations. NO_2 concentrations cause the atmosphere to have a different color because this gas is strongly absorbent over the blue-green area of the visible spectrum. This absorption produces illumination which is overbalanced toward the yellow-red end of the spectrum and gives NO_2 mixtures in air their characteristic yellow-brown coloration in proportion to the NO_2

concentration. Light absorption by NO_2 has been tabulated and demonstrated graphically from data given by Leighton (Ref 60). In order to determine the attenuation effect of NO_2 at a given wavelength, the gaseous extinction coefficient is related to the atmospheric concentration. It is unlikely that an observer would be aware of a target coloration when the concentration of NO_2 is about 0.1 ppm. However, at 1 ppm color effects would probably be quite marked and even at 0.25 ppm would most likely be noticed if the target were white.

Health effects of NO_2 and other oxides of nitrogen range from odor, nose and eye irritation, pulmonary congestion, edema, obliterative bronchiolitis and pneumonitis to death. However, mild effects from NO_2, such as mucous membrane irritation, do not occur at presently encountered overall air pollution levels. However, on a micro scale, such as in an enclosed area, the concentrations could build to a dangerous level.

The threshold limit value for NO_2 is 5 ppm. However, the State of California, Department of Public Health, has set an ambient air quality standard for NO_2 at 0.25 ppm, primarily on the basis of coloration effects which a concentration of this magnitude would be expected to cause in an area that otherwise would not be severely affected by pollutants (Ref 61). NO_2 concentrations in the ambient atmosphere range from 0.01 to 0.20 ppm with the mean being approximately 0.04 ppm (Ref 62).

Nitric oxide (NO) is of little toxicological interest as an air pollutant because of its relatively rapid conversion in the atmosphere to NO_2 ($2NO + O_2 - 2NO_2$). It has been shown that 50% of the NO emitted from the exhaust of an automobile during deceleration (4,000 ppm) is converted to NO_2 in 1 minute (Ref 57). The interest is primarily that of the increase in NO_2 concentration due to NO emission.

In areas where ozone concentrations are high, NO_2 is readily oxidized to N_2O_5 ($2\ NO_2 + O_3 \rightarrow N_2O_5 + O_2$) which is subsequently hydrated to nitric acid. Nitric acid is also formed in fog by the reaction $4\ NO_2 + 2\ H_2O + O_2 \rightarrow 4\ HNO_3$. The effects of nitric acid droplets in the atmosphere include impairment of health, property damage, and reduction of visibility.

Oxides of nitrogen emitted by aircraft engines consist primarily of NO with lesser quantities of NO_2.

Particulate Matter

In this study, the term "particulate" is used to describe pollutant materials in the solid state. Pollutants emitted in the form of liquid droplets are generally organic in nature and are included under organics. This method of classification avoids problems associated with condensation of organic vapors in engine exhaust gases. The concentrations of organics and solid particulates are not affected by changes in the physical state of organic materials.

Particulate matter emitted by automobile engines consists primarily of lead compounds in a wide range of particle sizes, from 0.02 to over 1.0 micrometers (Ref 69). Aircraft piston engines also emit lead compounds in particulate form since aviation gasoline contains tetraethyllead and halogenated scavenging agents in quantities similar to those in automobile gasoline. To the knowledge of the authors, the physical state of lead emissions from aircraft engines has not been reported. It is reasonable to assume, however, that the particle sizes of lead emissions from aircraft are similar to those from automobiles, but with higher concentrations of particles in the smaller size ranges. Since aircraft exhaust stacks are relatively short, there is less opportunity for particle agglomeration. Agglomeration of small particles in the exhaust system probably is an important mechanism for the formation of particles in the larger size ranges.

The toxicity of lead and lead compounds is well established. However, no health effects have been attributed directly to engine emissions. Nevertheless, considerable concern exists about the possible effects of lead emissions and a basis is being sought for establishing air quality criteria with respect to lead compounds.

Solid particulate matter emitted by aircraft turbine engines consists primarily of carbon particles. These particles are emitted in particle sizes in the range of 0.01 to 0.1 micrometers and are similar to carbon emissions from other types of combustion equipment. Pure carbon is considered to be relatively harmless from the health standpoint, and its principal effect as a pollutant is reduction of visibility. Deterioration of visibility as a result of emissions from aircraft turbine engines has been reported by several workers (Refs 63, 64, 65, and 66). The visibility of the engine exhaust plume itself is an esthetic problem quite distinct from the problem of general atmospheric pollution. (With military aircraft, exhaust plume visibility is also a tactical problem.) Exhaust plume visibility is discussed separately in a later section. It is recognized that carbon particles can have indirect effects as carriers of organic materials and odors (see Appendix II). However, these effects are complex and not well understood.

The nature of solid particulate matter other than carbon in turbine engine exhausts has not been investigated thoroughly. We are not aware of adverse effects from such materials except for the physical problems of visibility reduction and soiling. In this respect, their effects are similar to those of carbon particles. Consequently, for purposes of this study, solid particulate emissions from aircraft turbine engines have been assumed to consist totally of carbon particles.

Sulfur Dioxide

Sulfur dioxide is present in exhaust gases from both aircraft piston and turbine engines, but in lower concentrations than in gases from other types of combustion equipment. It stems from the combustion of sulfur compounds which are contained in all aircraft fuels as impurities. SO_2 is emitted as a colorless gas and can have a variety of adverse effects on health, including irritation of the respiratory system. In the atmosphere, SO_2 is converted to sulfur trioxide and sulfuric acid. The latter material also is an irritant, but has additional effects including reduction of visibility and damage to plants and property.

Visual Appearance

Most of the gaseous components of aircraft engine exhausts are colorless and, therefore, are not visible. As mentioned above, NO_2 is orange in color, but it is not present in sufficient concentration to impart color to engine exhaust gases.

The quantities and physical characteristics of particulate matter in piston engine exhausts are such that these also are invisible.

Consequently, under most conditions, the exhaust plumes from aircraft piston engines are not visible. At idle conditions, these engines emit a fog of unburned fuel which can be observed from close range, but in general, their visual appearance is not objectionable.

Exhaust gases from some turbine engines contain sufficient quantities of particulate matter to render the exhaust plume visible, even at long range. The principal offender is carbon which is created in combustion systems in a form which is highly visible. The visibility of the exhaust plume is affected primarily by the concentration of carbon in the exhaust gases, the arrangement of engines, and the aircraft speed. As will be noted later, carbon emission is affected by engine design and operating conditions, with carbon concentration generally increasing with power level. Exhaust gases from engines mounted close together tend to merge and become more visible than individual plumes. Similarly, plumes from aircraft traveling at low velocities tend to be more visible because the density of emission along the flight path varies inversely with velocity. As a result of these various factors, turbine engine exhaust plumes are most visible during take-off and climb-out operations, and the visibility of plumes from certain medium-range transport aircraft is aggravated by the clustering of engines on the fuselage. Meteorological conditions also affect exhaust visibility in that the plume is most evident on clear days and less so in the presence of atmospheric haze.

The visibility of an aircraft engine exhaust plume is considered to be an undesirable factor quite distinct from the contribution by the aircraft to community concentrations of particulate matter. Consequently, reduction of exhaust gas carbon concentrations is a matter of concern from the standpoint of plume visibility and methods of measuring this characteristic are discussed along with other measurement techniques in Appendix I. It should be stressed, however, that an exhaust plume may be rendered invisible but the emission of particulate matter by the engine may still be significant from the standpoint of community air pollution.

Odor

Odors resulting from the operation of aircraft turbine engines frequently are noticeable in air terminals. These odors are generally objectionable and are regarded as an adverse sensory effect. At present, substances which are responsible for odors from aircraft have not been identified precisely, nor are the mechanisms of odor production well understood. In addition, there are no straightforward methods of measuring odor intensity. The response of human subjects is the only method currently used for measuring odors. Even though odors at air terminals are associated with aircraft activity, it does not necessarily follow that odor intensity is proportional to activity levels. Thus, it is clear that odor represents an effect which should be eliminated, but effective approaches to odor reduction do not exist at the present time. The characterization and measurement of odors are discussed in Appendix II.

Formation of Pollutants in Aircraft Engines

General

In aircraft engine combustion chambers, and most other internal combustion devices, the processes by which pollutant species are formed can be grouped into two general categories. These are (1) bulk processes, or "normal" combustion processes, and (2) quenching processes, or "inhibited" combustion processes. Bulk processes are those which occur in regions of the combustible medium which are not directly affected by the presence of the chamber walls or other factors which could disrupt the chemical and physical processes leading to complete combustion. In bulk processes, the composition of the combustion products, including the concentrations of pollutants, is determined by the composition and physical conditions (temperature, pressure, uniformity, etc.) of the initial, unburned mixture.

Quenching processes, on the other hand, are those which occur in regions of the combustion chamber where combustion is inhibited by various mechanisms. The principal inhibiting mechanism is cooling, which occurs by convection at the walls of the chamber, and by dilution in regions where cooling air is introduced. In these regions, combustion processes are partially or completely inhibited, resulting in a different product composition, and different concentrations of pollutant species.

Piston Engines

Aircraft piston engines, like automobile engines, operate at fuel-rich mixture ratios under all conditions except cruise, and air terminal activities consist almost entirely of non-cruise operating modes. As a result, the products of normal combustion, or the bulk processes, contain a substantial portion of carbon monoxide (CO). This condition is even more severe with turbo-charged engines in which excess fuel is used to reduce exhaust gas temperature. In these cases, bulk combustion processes also produce high concentrations of unburned hydrocarbons (organics) in the exhaust gases.

Nitrogen oxides (NO_x) also are produced by bulk processes, though the actual mechanisms are not completely understood. Fuel-rich operation tends to reduce the output of nitrogen oxides since less oxygen is available to combine with the nitrogen in the air. Consequently, the dependence of NO_x production on fuel-air ratio, in general, is opposite to that of CO and organic production.

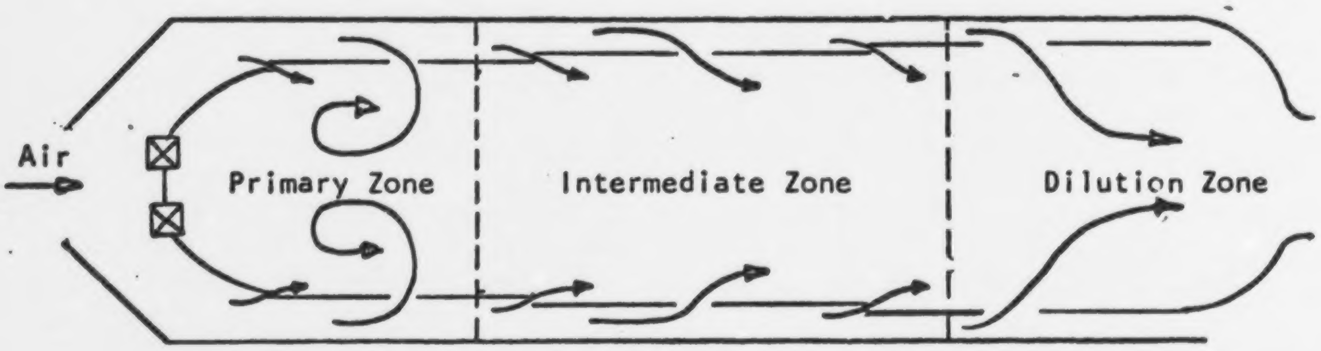
The principal quenching process in piston engines is the cooling effect of the chamber walls. During each cycle, a thin layer of fuel-air mixture adjacent to the walls and in confined spaces, such as cylinder-head joints, does not burn. The fuel contained within this quenched volume is discharged to the atmosphere along with the products of normal combustion and gives rise to a substantial concentration of hydrocarbons. These substances pass through the engine largely unchanged and, consequently, their composition is similar to that of the original fuel.

The piston engine produces only small quantities of particulate material, and a major fraction of what is produced consists of lead compounds. As with automobile fuels, lead is added to aviation gasoline to eliminate detonative combustion (knock), and most of the lead added is emitted to the atmosphere as solid particles of lead chloride, lead bromide, and other compounds.

Turbine Engines

In contrast to piston engines, gas-turbine engines operate at lean over-all fuel-air ratios. Theoretically, complete combustion can be obtained and pollutant emissions associated with bulk processes eliminated. Indeed, it is well-known that emission levels of turbine engines are substantially lower than comparable piston engines. However, design requirements (for example, ease of ignition, stable operation over a wide range of over-all fuel-air ratio, maintenance of tolerable metal temperatures by use of only combustor inlet air as a coolant, and high combustion efficiency at cruise conditions) dictate that local fuel-air ratios and temperature levels be highly nonuniform within the combustor and vary widely with operating conditions. As a result, gas-turbine combustors generally contain regions of incomplete combustion, the extent of which are highly dependent upon the detailed design of the combustor as well as the engine operating condition.

A gas-turbine combustor can be conveniently described in terms of three zones, as indicated in the sketch below:



The primary zone of the combustor, in which the fuel is atomized, heated, mixed with air, and partially burned at near-stoichometric conditions, tends to contain fuel-rich regions. This condition leads to partial combustion at high temperature and the production of solid carbon particles (smoke) and carbon monoxide. In the secondary zone, in which air is added relatively slowly to reduce dissociation losses, further oxidation of incomplete combustion products occurs; however, this oxidation is never sufficient to eliminate carbon particles if they are formed in the primary zone. Oxides of nitrogen are formed in both primary and secondary combustion zones.

Quenching of unburned fuel occurs in the primary zone near the chamber walls. However, the amount of unburned fuel produced in this manner is relatively small since the surface area is small compared to that in the piston engine. Quenching of partially-burned fuel and carbon monoxide can occur in the secondary zone by too-rapid dilution with secondary air. However, in current combustors, quenching by dilution has been reduced to a very low level.

Because of the differences in operation between piston and turbine engine combustors, the concentrations of pollutants in their exhaust gases also are different. Rates of emission of various pollutants are discussed in the next section.

Rates of Pollutant Emission by Aircraft Engines

In this section, the rates of emission of various pollutants by individual engines will be discussed. To provide a basis for comparing emissions from different engines and for computing total emissions, the emission rate of each species is expressed as an emission index as defined by Sawyer and Starkman (Ref 67). The emission index is the weight in pounds of pollutant emitted per 1000 pounds of fuel consumed. For comparison purposes, the use of emission indices can be justified on the basis that most internal combustion engines have comparable thermal efficiencies, and thus, the emission index is a measure of pollutant emission per unit of power output or work done. From a practical standpoint, the emission index allows a direct conversion of fuel consumption to pollutant emission.

Piston Engine Emissions

At the present time, very little direct information is available on the rates of pollutant emission by aircraft piston engines. During this study, the only data found on aircraft piston engine emissions consisted of exhaust gas measurements for one engine (Pratt & Whitney R2800) at two operating conditions (Ref 68). Consequently, it has been necessary to rely upon emission data from automotive engines in order to evaluate pollutant emission from piston-engine aircraft. The use of automobile data introduces an uncertainty into the calculated emission loads. However, the limited data for aircraft engines appear to be consistent with data for automobile engines.

Pollutant emission rates for automobiles often are published in terms of average rates over an extended period of time, distance, or over a typical cycle of operating conditions. Such data are not sufficient for evaluating aircraft emissions since the modes of operation of an aircraft engine during a landing and take-off cycle differ substantially from the operating modes of a typical automobile cycle. Therefore, it is necessary to determine emission rates for each of the different operational modes and to evaluate the pollutant load for each mode separately.

The pollutants of principal concern from piston engines are:

1. Carbon monoxide
2. Gaseous organic compounds
3. Oxides of nitrogen
4. Particulates

Particulates consist mainly of lead compounds, and, when expressed as a fraction of the fuel consumed, the rate of particulate emission is directly proportional to the lead content of the fuel, and is largely independent of operating mode. (The latter statement is not entirely true with automobile engines due to accumulation of lead in the exhaust system during low-power operation. However, lead accumulation is far less likely in an aircraft engine since the exhaust stacks are short and less time is spent in low-power modes.) Reported values of particulate emission rates for automobiles range from 0.00078 lb/lb-fuel (Ref 69) to 0.0020 lb/lb-fuel (Ref 3). Since the average lead content of aviation gasoline is higher than that of automotive gasoline, and the retention of lead compounds in the aircraft engine probably is less, the higher emission rate (0.002 lb/lb-fuel) is assumed to be representative of aircraft piston engines and has been adopted for use in this study.

The emission rates of other pollutants are not directly proportional to fuel consumption rate, but are affected strongly by engine operating conditions. The principal factor affecting the exhaust gas composition is the air-fuel ratio. Data from various sources on emission rates of CO, organics, and NO_x as functions of air-fuel ratio are shown in Figures 11, 12 and 13. These data are from uncontrolled automobiles, that is, automobiles not incorporating emission control devices.

The CO emission data in Figure 11 show a rapid increase in emission rate with decreasing air-fuel ratio. The data are in reasonable agreement for part load conditions, but emission rates at idle conditions appear to be substantially lower. The two operating points for the PWA R-2800 engine are consistent with the automobile engine data.

Data from various sources on organic emissions do not agree well, probably because different analysis techniques have been used by different investigators. The data on organic emission from the PWA engine were given in volumetric units with no indication of chemical composition. Through chemical element balance computations, the average carbon number for the organic emission was found to be 3.9. Assuming an average composition of $(CH_2)_{3.9}$ and converting to weight units, the data for this engine were found to agree well with the data reported by Neerman and Millar (Ref 76) which were obtained by mass spectrometer analysis. A correlation curve has been drawn through the PWA and Neerman and Millar data from which emission rates have been taken for use in this study.

Fair agreement is found among data from various sources on nitrogen oxide emission. At air-fuel ratios less than 10, the emission rate is assumed to be negligible. At higher A/F values, the Huls data (Ref 70) have been used to obtain values for this study.

Air-fuel ratios at various engine operating conditions are shown in Figure 14 for fuel supply systems for two typical aircraft piston engines (Ref 8). Also shown are selected operating points for five radial engines manufactured by the Pratt & Whitney Aircraft Corporation (Ref 68). Air-fuel ratio is plotted against air-flow rate which is approximately proportional to power output. The data shown are for the "full rich" condition at which the mixture control adjustment is in the extreme rich position. Piston-engined aircraft usually are operated at the full rich condition during operating modes associated with landing and take-off. The leaning adjustment is employed during cruise conditions to obtain more economical air-fuel ratios. (See Aircraft Fuel Systems).

From Figure 14 it can be seen that wide variations in air-fuel ratio exist for different engines and operating conditions. This is particularly true under idle conditions. Since, as we have seen, pollutant emission rates vary strongly with air-fuel ratio, pollutant emission also will vary widely among aircraft. In this study, in order to determine pollutant loads at air terminals, it has been necessary to classify aircraft by type and to assign average rates of pollutant emission to each type. Using the emission and operating data presented here, typical emission rates have been selected for use in estimating pollutant loads. These typical rates are listed in Table 40. It must be kept in mind, however, that emissions by individual aircraft can vary considerably from these levels.

The operational data presented in Figure 14 were obtained from large, radial engines. In assigning emission rates to small piston engines (class 6 aircraft), it has been assumed that they are operated at conditions similar to those of the larger engines, and that their rates of pollutant emission, on a lb/lb-fuel basis, also are similar. No data on operational air-fuel ratios or emission rates have been obtained for light engines. Available information on operating conditions does indicate, however, that air-fuel ratios at take-off are higher with light, unsupercharged engines than with heavier engines (Ref 77). This difference in take-off condition is included in Table 40, whereas conditions at all other operating modes are assumed to be similar for all piston engines.

It has been pointed out throughout this discussion that uncertainties exist as to the validity of the emission rates which have been assigned to aircraft piston engines. An additional source of uncertainty is the possibility of afterburning, that is, spontaneous combustion of the engine exhaust gases after emission to the atmosphere. There is reason to believe that afterburning does occur under certain operating modes, but the extent of afterburning is unknown. In automotive engines, injection of air into the exhaust manifold is found to be an effective method of reducing CO and organic emissions, while little effect is noted on NO_x emission (Ref 73). Because aircraft piston engines have shorter exhaust stacks, exhaust gases enter the atmosphere at a relatively high temperature. As a result, afterburning may occur during certain operating modes and the effective emission rates of CO and organics during these operations may be less than those shown in Table 40. Consequently, the emission rates used in this study for piston engines may be regarded as conservative.

Turbine Engine Emissions

In contrast to aircraft piston engines, considerable information exists on pollutant emissions from aircraft turbine engines. Results of three studies of turbine engine emissions have been published containing emission indices for various pollutants (Refs 78, 79, and 80). In addition to these data, aircraft engine manufacturers have measured emissions from their own engines and have provided emission data for use in this study (Refs 55, 56, 81, 82 and 83).

Pollutants of concern from turbine engines are:

1. Carbon monoxide
2. Organic compounds
3. Oxides of nitrogen
4. Particulates
5. Sulfur dioxide

As with piston engines, the emission indices (lb/1000 lb-fuel) of CO, organics, and NO_x are not constant for turbine engines, but vary with engine design and operating conditions. Particulate emission also is variable with turbine engines and consists mostly of carbon (soot). This is in contrast to particulates from piston engines which consist mostly of lead compounds. SO_2 emission is of concern for turbine engines because their fuels contain a small, but significant, amount of sulfur. The SO_2 emission index is directly proportional to the sulfur content of the fuel which, for aviation kerosine, is approximately 0.05 per cent. Using this value, the SO_2 emission index is 1.0 lb/1000 lb-fuel.

Emission indices for CO, organics, NO_x, and particulates, derived from the data from the sources indicated above, are listed in Table 41. Emission indices are presented for three operating conditions--minimum, intermediate, and full power--which correspond approximately to the idle, approach, and take-off aircraft operational modes. The data are grouped according to the three basic types of turbine engines--turbojets, turbofans, and turboshaft engines--and the test conditions and fuels used are included in the table. Identification of the engines tested has been omitted at the request of the Aerospace Industries Association of America, Inc. (Ref 84).

The emission indices in Table 41 are presented graphically in Figures 15a, b, c and d. It is apparent from these figures that reported emission rates vary widely between engine classes and between engines of the same class. Variations in emission rates also are observed between different engines of the same model. It is likely that these differences stem partly from differences in sampling and analysis techniques.

In spite of the dispersion of the data, certain trends are apparent. For all engine classes, CO and organic emissions are high at idle conditions and low at part and full power. This effect is attributable to a degradation of combustor performance at low power. NO_x and particulate emissions, on the other hand, increase with power level. These increases are related to increases in combustor temperature and pressure, but the exact mechanisms of NO_x and carbon formation are not known.

No attempt has been made to correlate these emission data with specific engine operating variables, because, in the opinion of the authors, no causative relationship exists between the emission index for any pollutant and any of the primary engine operating variables. Emission levels are dependent upon characteristics of the engine combustion system which are only indirectly related to the primary variables such as fuel rate, air rate, or engine speed. Effects of engine design on pollutant emissions are discussed later in the section on reduction of emissions.

In selecting emission data for use in calculating emission loads at air terminals, one engine was selected as representative of each aircraft class (see Table 1). In most cases, the engine selected is in service in most of the aircraft in its class. Emission indices for each representative engine, as reported by the engine manufacturer, were assumed to be typical of all engines in the same aircraft class and were used to calculate pollutant emission loads for all aircraft in that class. This approach was used in all cases except that average NO_x emission indices for all turbine engines were used for aircraft classes 1, 2, 3 and 7, and indices for CO and organic emission for class 4 aircraft engines were also used for class 7 aircraft engines. The approaches used in these special cases were necessary because of a lack of data or uncertainties in the data for various engines.

The emission indices used to calculate quantities of pollutants emitted during aircraft operations are listed in Table 40. This table allows a comparison of emission indices for piston and turbine engines. It is observed that indices for CO and organic emission for turbine engines are substantially lower than those for piston engines, particularly at intermediate and high power levels. However, indices for NO_x and particulate emission are of comparable magnitudes for all engine types.

Quantities of Pollutants Emitted by Aircraft Engines

Individual Engine Emissions

Quantities of pollutants emitted by aircraft engines, referred to here as emission loads, have been calculated from data presented earlier in this report. The method of approach employed is first to determine the quantity of pollutant produced by an engine when it is operated through a set series of operations. These operations are chosen to represent those that occur during a typical landing and take-off cycle for an aircraft employing the engine (see Table 2). Four major pollutant species are considered, these being carbon monoxide, organics, oxides of nitrogen, and particulate matter. In addition to determining the total quantities produced during an LTO-cycle, those produced during individual operational modes are also determined. The four modes of operation are:

1. Idle
2. Taxi
3. Ground runs on landing and take-off
4. Approach and climbout

Emissions of sulfur dioxide are considered separately. It is emitted in relatively small quantities and only total emission figures are given.

The aircraft classification system described in Table 1 separates all aircraft into seven categories and indicates the engine present in the greatest number in each class. The calculation outlined above has been carried out for all seven engines. The results, given in Table 42, show that large piston engines (class 5 aircraft) produce the greatest quantities of carbon monoxide and hydrocarbons whereas turbine engines (classes 1, 2, 3 and 7) produce greater quantities of nitrogen oxides. The relative capabilities of all engine types to produce pollutants are shown in Table 43 where a comparison is made of emission loads from various engines with those from a large turbine engine. Table 43 also contains similar comparisons by aircraft type and allows for the difference in number of engines per aircraft.

Emissions at Air Terminals

Pollutant loads at several air terminals and in certain urban areas have been determined from the engine emission data presented above. A count has been made of all aircraft activity by aircraft type occurring at the air terminals of interest. From a knowledge of the number of engines each aircraft contains, it is possible to express activity in terms of the number of engines of each category that pass through the airport (See Table 24). It has been assumed that all engines in each class emit pollutants at the same rate as the representative engine for that class, and total airport emission loads have been determined by combining the activity levels with the calculated emission loads for individual engines (Table 42).

Results for an average day during 1967 are summarized in Tables 44, 45, 46, and 47 as follows:

	Terminal or Area
Table 44	J. F. Kennedy Teterboro New York City Area
Table 45	Washington National Washington Area
Table 46	Los Angeles International Longbeach Los Angeles County
Table 47	All FAA-Controlled Terminals

Terminals included in the urban areas are listed in Tables 21, 22, and 23. Emission loads listed in these tables are summarized in Table 48 with emissions during ground and flight operations shown separately.

Total Emissions by Aircraft Engines

The total quantities of pollutants emitted by aircraft engines in the United States are of interest and can be estimated from the information presented in this report. However, our knowledge of aircraft acitivity is insufficient for an accurate calculation of the total pollution produced across the nation by aircraft. Activity at FAA-regulated air terminals is well documented, but information on activity at military air terminals is available only in terms of the total number of landing and take-off cycles per year and not by aircraft type. Activity at private airports is not reported at all, but is believed to represent less than 10 per cent of the total national activity.

To estimate the total quantities of pollutants emitted by aircraft, emissions during cruise operations and air terminal operations were estimated separately. Fuel consumption data presented earlier indicate that approximately 80 per cent of all fuel is consumed during the cruise mode. Using fuel consumption data and emission indices corresponding to cruise conditions, estimates of emissions during cruise have been made and are listed in Table 49.

Emissions from civil aircraft during air terminal operations were taken from Table 48. (Civil activity at non-FAA-controlled terminals was neglected.) Emissions from military aircraft were estimated using published data on military activity (Table 20) and an estimated distribution of aircraft types presented earlier (see Aircraft Population). The estimates of emissions from cruise and air terminal operations are combined in Table 50 to indicate the approximate rates of pollutant emission by all aircraft operations in the United States.

Error Analysis

The elements used and the assumptions made in the calculation of emission loads are listed in Table 51. Errors resulting from the use of aircraft activity data and engine fuel consumption rates are believed to be small, except perhaps in the calculation of pollutant emission at military air terminals where the need arises to estimate the distribution of aircraft by type. However, more substantial errors could arise from the assumptions relating to engine emission rates and the duration of the idle operational mode. On the basis of the dispersion of pollutant emission data for both piston and turbine engines, it is estimated that actual emission rates may exceed those used in this study by as much as 100 per cent. It is also estimated that the duration of engine idling operations, particularly during busy hours (10 am to 10 pm), may exceed the value used here (1 minute) by factors between 10 and 30. The effects of these variations on engine emission loads during an LTO-cycle are shown in Table 52.

Maximum Possible Emission Loads

Previous estimates of emission loads have been based upon average operating conditions, that is, average activity levels, mean landing and take-off cycles, and in some cases, mean pollutant emission rates. Appreciable departures from average activity levels do occur at times at all terminals. Table 53 shows the maximum variations that occur at the airports of interest in this study. The variations are expressed as ratios of peak hourly activity to average hourly activity, and values of three are typical for large air terminals.

Activity ratios can be used together with the error factors produced in the previous section to estimate the maximum possible emission loads at the major airports. Clearly, idle time is a function of relative activity level and can be expected to increase rapidly as the level increases. At peak-hour activity, average idle time can increase to 30 minutes. This figure has been used together with the peak-to-average activity figure and increased emission indices to determine the maximum possible emission loads at J. F. Kennedy air terminal. The results, given in Table 54, show that it is quite possible for hourly emission loads to exceed the average loads given in Table 44 by factors ranging from 5 to nearly 20.

Future Trends in Aircraft Engine Emissions

Changes in the nature and extent of aircraft exhaust emissions in future years will occur as a result of changes in aircraft activity levels and changes in equipment. The effects of these changes cannot be predicted accurately, but certain impending changes can be identified and their probable effects noted.

Activity levels are expected to increase in all aviation categories at the rate of approximately 10 per cent per year. Consequently, pollutant emission can be expected to increase accordingly on a daily average basis. Peak-hourly rates will not follow the same trend at major air terminals due to limitations on activity levels of conventional, fixed-wing aircraft. Limitations on LTO-cycle frequency have been imposed on several major terminals by the FAA and it does not appear that these limits will be lifted in the near future.

Another form of aircraft activity is appearing which will occur along with conventional activity, and that is STOL and VTOL aircraft activity. STOL aircraft are being introduced in the Northeast corridor on an experimental basis and it is reasonable to expect that they will enter regular service in the near future. STOL activities probably will not displace conventional activities, since they utilize separate landing areas.

Principal changes in aircraft equipment anticipated in the near future are:

1. Retirement of piston-engine, transport aircraft
2. Introduction of large, turbine-engine, transport aircraft
3. Increased use of turbocharged, piston engines in general aviation aircraft

Decreased use of piston-engine transport aircraft will gradually eliminate the largest individual sources of CO and organic emission among aircraft. These will be replaced with current models of turbine-engine aircraft mostly of the Class 2 category. The principal effects of this replacement will be a decrease in CO and organic emission and an increase in NO_x emission during operations at air terminals.

New, super-size transport aircraft, such as the Boeing 747, Lockheed 1011, and McDonnel-Douglas DC-10, will be in service in the early 1970's. Fuel consumption rates of these aircraft will be 30 to 40 per cent greater than those of current transport aircraft. However, pollutant emissions are not expected to increase accordingly. Current efforts by engine manufacturers to reduce exhaust plume visibility will result in a reduction in particulate emission by individual aircraft. Also, the use of annular combustion chambers in the "jumbo-jet" engines will result in reduced CO and organic emission. On the other hand, emissions of oxides of nitrogen by the new aircraft are expected to increase.

There is a trend in the production of general aviation aircraft toward increased use of turbocharged, piston engines to provide greater take-off power and higher altitude capability. CO and organic emission rates are greater for turbocharged engines at take-off conditions. Consequently, emission of these pollutants by general aviation aircraft is expected to increase.

To indicate the effects of changes in activity and equipment on pollutant emission by aircraft engines, estimates of emissions from civil aircraft in the year 1979 have been prepared. These estimates are listed in Table 55 and are compared with emissions from civil aircraft in 1967.

Emissions from military aircraft have been omitted from these projections since military activity in 1979 cannot be predicted reliably from current trends.

The future trends in aircraft emissions listed in Table 55 were calculated using the following assumptions:

1. Activity in aircraft classes 1, 2, 4, 5 and 7 will increase in proportion to FAA projections of air carrier aircraft in those classes (Table 9), and total activity in these classes will equal projected air carrier activity in 1979 (Table 20).

2. Activity in aircraft class 6 will increase to the level projected by the FAA for general aviation aircraft in 1979 (Table 20).

3. In 1979, aircraft classes 1 and 2 will consist of equal numbers of current aircraft models and new "jumbo jets". Emission indices (not emission rates) for the engines of the new aircraft will be one-half of current values for CO, organics, and particulates, and $1\frac{1}{2}$ times current values for NO_x emission.

4. In 1979, all class 6 aircraft will be powered by turbocharged engines and their emission indices will be changed from current values by the following amounts: CO - 10 per cent increase, organics - 30 per cent increase, NO_x - 20 per cent decrease, and particulates - no change.

5. Finally, it has been assumed that no controls on emissions from aircraft have been instituted by either Federal, state or local authorities.

Summary

In this section, the characteristics of pollutants emitted by aircraft engines have been described, and the mechanisms by which these materials are formed have been discussed. The rates of pollutant emission by individual engines have been presented, and this information has been used, along with activity and fuel consumption data from previous sections, to estimate quantities of pollutants emitted at air terminals. Finally, future trends in pollutant emission by aircraft engines has been discussed. Certain pertinent observations have been made from the material presented in this section and are as follows:

1. Pollutants of primary concern emitted by aircraft engines are carbon monoxide, organics, nitrogen oxides, lead compounds, and carbon (soot). Sulfur dioxide is emitted in relatively small quantities by both piston and turbine engines and is of secondary concern.

2. Aircraft piston engines, on a nationwide basis, account for most of the emissions of CO and organics by aircraft. However, at certain air terminals, turbine-engine aircraft emit greater quantities of these materials because of the preponderance of activity by these aircraft.

3. Aircraft turbine engines, individually and collectively, emit greater quantities of NO_x than aircraft piston engines.

4. Anticipated changes in aircraft equipment will change the rates of pollutant emission from individual engines. However, the total quantities of all pollutants emitted are expected to increase substantially in future years.

The discussion in this section and the observations made pertain to aircraft engine exhaust emissions only. Other emissions resulting from aircraft activity, such as those from auxiliary power units, have not been included but may be significant.

In the next section, the effects of aircraft emissions on the public will be discussed. Quantities of pollutants emitted by aircraft engines will be compared with emissions from other sources.

IMPACT OF AIRCRAFT ENGINE EMISSIONS

This section is a report of factors influencing the effects or impact of aircraft engine emissions, a consideration of the localized effects of these emissions, and an evaluation of the relative importance of aircraft engine emissions in total urban air pollution in the Los Angeles, New York, and Washington metropolitan areas. In order to provide a quantitative basis for the analysis of impact, a simple emission and diffusion model for aircraft operations during an LTO-cycle has been developed. This model has been used to predict concentrations of four major types of contaminants in air terminal areas and in the immediate neighborhood of airports. Also, gross estimates of the importance of aircraft emissions have been calculated by comparing the amounts of certain pollutants emitted by aircraft to the amounts of the same pollutants arising from other sources in the vicinity of air terminals and elsewhere within metropolitan areas.

An independent measure of the significance of environmental contamination caused by aircraft emissions is available from the records of public complaints involving air pollution in the vicinity of major air terminals. Such data are necessarily subjective, but they can be helpful in the determination of geographical limits and possible trends in the detection of undesirable atmospheric conditions by the exposed population. For the present study, records of public complaints of air pollution from aircraft have been analyzed and the results of this analysis are presented in Appendix III. Changes in land use near air terminals have also been investigated; such changes may indicate an adverse reaction to environmental quality in these areas.

Factors Influencing Impact

Locations of Airports with Respect to Homes, Businesses, and Central Parts of Cities

The location of an air terminal relative to other components of the metropolitan area is important in the determination of the impact of aircraft engine emissions. Ambient concentrations of pollutants emitted from a defined source area (such as an airport) will decrease as the distance from the source increases. The principal mechanism for diffusion, and therefore dilution, of air-borne contaminant material is atmospheric turbulence, or eddy mixing. The diffusion rate depends upon the intensity of atmospheric turbulence, and the turbulence intensity in the lowest part of the atmosphere is determined by the vertical temperature distribution and by the roughness of the lower boundary (e.g., flat land, tree covered land, buildings, roads, hills, etc.).

The urban area immediately adjacent to an airport is the highest-risk region for airport-based emissions. Thus, the possible impact of aircraft emissions is related to land use in the vicinity of the airport. When the airport neighborhood is primarily residential, the local population will be subject to maximum exposure; when the typical land use is commercial or industrial, the projected exposure to the population (e.g., workers, 40 hours per week) is significantly lower. Obviously an "open area" of unused land around airports would minimize the possible impact of aircraft emissions upon the urban population. (The statements in this paragraph illustrate general principles only; they are not intended to suggest the necessity of land-use controls in the vicinity of existing airports.)

It is also evident that the possible impact of airport area emissions upon an urban population is greatest when regions of maximum population density are relatively near the airport (within five miles, for example) and downwind from the airport for the prevailing wind directions. However, area-wide emission rates for contaminants at major metropolitan airports, discussed later in this section, are comparable to, or less than, the emission rates for the same contaminants elsewhere within the subject cities. Thus the specific impact of aircraft area emissions would be difficult to detect or evaluate at downwind distances greater than a few miles.

Table 56 contains a summary of land use characteristics within approximately three miles of J. F. Kennedy International Airport, Washington National Airport, and Los Angeles International Airport. Although the tabulated information indicates significant land use near the airport, it should be noted that important open areas exist adjacent to each airport: ocean coastal waters in New York and Los Angeles and the Potomac and Anacostia Rivers in the capital area.

The J. F. Kennedy Airport is located on the south shore of Long Island 13 miles southeast of midtown Manhattan and 3-1/2 miles north of the Atlantic Ocean. It comprises an area of 7 square miles and is at an elevation of 22 ft MSL. The airport is bounded on the southeast through southwest by Jamaica Bay and numerous salt marshes. A range of hills, 100 to 300 ft in elevation, lies east-west along the major axis of Long Island; at their nearest point they are 4 miles to the north of the airport. Areas west through north and to the east are heavily populated and industrialized.

The Washington National Airport, comprises an area of 1 sq mile at an elevation of 16 ft MSL and is located on the west bank of the Potomac River 3 miles south of the urban center. With the exception of the Potomac on the east, it is in close proximity to urban activity. The relatively flat Atlantic Coastal Plain extends eastward 50 miles to the Chesapeake Bay and 100 miles to the Atlantic Ocean. The nearest mountains, the Blue Hills 50 miles to the west, rise to elevations near 2,000 ft and the Appalachian range is 100 miles to the west. There are hills 200 to 400 ft in height within 4 to 6 miles in most directions from the airport.

Los Angeles International Airport is at 99 ft MSL. The coastline is approximately northwest-southeast about three miles west of the airport center, but it extends west from Santa Monica to the north and southwest 14 miles to the south. The main business district of the city is 11 miles northeast. Homes and business developments are located 0.5 miles to the east and 0.3 miles to the north. Oil wells and oil refineries are located south of the airport boundaries. The terrain slopes gradually down to Los Angeles Harbor which is 15 miles to the southeast. The Baldwin Hills four miles to the north-northeast rise to about 600 ft, and low hills about 4 miles east reach elevations of 250 ft. The Puente Hills, 20 miles to the east, range from 1400 to 1500 ft and slope upward southeast into the Santa Ana Mountains. Twelve miles south of the airport, the Palos Verdes hills rise to an elevation of approximately 1200 ft.

Meteorology and Topography

General Principles

The lateral and vertical extent of the atmosphere available for waste (air contaminant) disposal is limited and is significantly influenced by meteorological and topographical effects. For a consideration of area source air pollution phenomena (instead of single point source problems) it is appropriate to express the "dilution capacity" of the lower atmosphere as the product of the local mixing layer depth and the average wind speed within the mixing layer. The mixing layer extends from ground level upward to some height (typically 500 ft) above which vertical mixing rates are significantly reduced. The mixing layer depth is controlled primarily by the local vertical temperature profile. When the temperature lapse rate is adiabatic (neutral stability), contaminants introduced to the atmosphere near ground level will mix rapidly throughout the neutral stability layer. When the lapse rate is less than abiabatic or zero (the isothermal case), the rate of vertical mixing is lower and the depth of the mixed layer is usually less.

During inversion conditions, mixing is usually suppressed everywhere above the base of the inversion. When ground level inversions occur for extended times, nearly all contaminants entering the atmosphere remain in the lowest few hundred feet above ground level.

The average wind speed in the mixing layer determines the local "ventilation rate". Ground level wind speeds are typically lower than elevated winds because of friction drag. Thus estimates of atmospheric dilution capacity based upon surface data only are generally conservative.

Ideally, wind speed data used for estimates of ventilation should be obtained from local vertical soundings.

In addition to the transport and dilution of contaminants by the wind field, other processes can change the character of substances after they enter the atmosphere. These processes include the photochemical creation of new species (e.g., NO_2 + light - NO + O; O + O_2 - O_3), other chemical changes (organic and inorganic), gravitational settling of larger particulate material, and the washout of material by precipitation.

Topography can induce local flow patterns which may significantly modify the transport and dilution or accumulation of air pollutants. Topography or "surface roughness", determines the generation rate for mechanically induced turbulence in the lower part of the atmosphere, and surface thermal differences cause variability in the rates of thermally-induced turbulence. Some of the topographic influences which are important for evaluating the impact of aircraft emissions include the channeling of flow through valleys, the persistence and intensification of inversions in valleys, circulations between land and water areas, urban-rural differences in surface roughness and thermal characteristics, and wind intensification on hills and ridges. Recent investigations concerning topographic and terrain influences upon air pollution phenomena have been reported by several investigators (Refs 85 through 97).

Because very little air quality data is available for airport areas, the analysis of meteorological and topographic effects upon the emission and transport of contaminants from aircraft engines must be based upon studies of general urban air pollution phenomena. It is reasonable to inquire whether such extrapolations are valid, in view of the special nature of large airport areas. For example,

(1) Is the physical setting or size of a large airport, considered as an area-source of contaminants, unique? (As an illustration, most airport emissions occur along the taxiways and the runways, and these areas are typically surrounded by flat, source-free land.)

(2) Are the micrometeorological conditions at an airport different from those elsewhere within an urban area?

(3) Do aircraft emissions, because of special chemical or physical properties, or because of their release above ground level, respond to meteorological influences in a unique manner? (For example, a typical exhaust jet is hot, and therefore buoyant, but it is directed horizontally or downward during take-off. Thus, it is not possible to take advantage of the momentum of the jet emission to improve vertical mixing and diffusion.)

(4) Are the transport processes in the atmosphere near an urban airport influenced primarily by small scale (local) meteorological conditions or by the larger scale (urban and synoptic scale) conditions? For example, some airports are located on the fringes of the metropolitan area where the microclimatology is essentially semi-rural. Mechanically induced turbulence is at a minimum, urban heat island effects are absent, and early morning inversions are pronounced. The John F. Kennedy Airport is semi-rural in these respects (Ref 98). On the other

hand, Washington National Airport is very close to the center of the urban heat island for minimum temperatures (Ref 99).

Climatological Summaries

The following summaries describe typical urban and synoptic-scale meteorological phenomena for New York City, Washington, and Los Angeles. An understanding of these larger scale conditions, which influence micro- and mesoscale transport and dilution processes within the local atmosphere, is necessary for the evaluation of the possible air pollution risks arising from aircraft operations within the three cities.

New York

The climate of New York City and nearby areas is a modified continental type, being influenced more by the land mass to the west than by the ocean to the east. It is characterized by a relatively high frequency of day-to-day weather fluctuations combined with a tempering oceanic effect.

A high frequency of low pressure systems is associated with the tracks of major storms moving with the prevailing westerly winds. Coastal storms are common in the cooler half of the year. In the months from April to September, J. F. Kennedy Airport experiences onshore winds in the sector from south-southwest to south-southeast with a frequency of 32 per cent.

Maritime influences act in several ways. There is a more uniform occurrence of precipitation throughout the year than is typical of an inland regime. Average minimum temperatures along the coast are higher than in the interior. The mid-afternoon sea breeze occurs during spring and summer in the New York harbor area and along Long Island, but it seldom penetrates more than 10 miles. The sea breeze in the New York area has been studied by Frizzola and Fisher (Ref 100).

The urban heat island of New York City has been studied recently by Bornstein (Ref 98). At the surface, the average urban heat island temperature excess is 2.9 degrees F, measured between urban and rural sites near sunrise. Typically, the temperature excess drops to zero at 300 meters altitude.

Kennedy airport is relatively uninfluenced by the heat island effect, and the airport area might be classified as non-urban. Synoptic soundings at the airport indicate a relatively high frequency of surface inversions near sunrise; within the central part of New York such inversions are elevated because of the excess surface heating.

Washington, D. C.

The Washington climate has the nature of both a continental and a maritime regime. This is reflected in the bimodal characteristic of the annual surface wind direction frequency distribution. The SW-S lobe of the annual wind rose reflects the strong maritime influence of the Atlantic high-pressure cell. The WNW-NNW lobe represents the continental regime of prevailing westerlies. These effects are also seen in the seasonal wind roses where WNW-NW winds predominate over the southerly flow in winter and where SSW-S winds are much more common in summer.

During summer, Washington is dominated by the strong southerly flow of warm, humid air from subtropical latitudes as storm tracks are displaced farther north. Cold fronts that dip southward deposit more precipitation during uplift over the Appalachian mountains than at Washington where the downslope effect is quite noticeable. Precipitation during this time of year is derived almost exclusively from showers and thunderstorms associated with either frontal or squall-like systems, or with air mass instability

As autumn approaches, storms of tropical origin, including hurricanes, may pass northeastward along the atlantic coastline to provide a significant portion (20-30 per cent) of the rainfall at this time of year. Large high-pressure areas may dominate the region in October or early November with associated warm, calm days and cool nights. Stagnating anticyclones occur more frequently during this time of year.

Late autumn and winter storms originating in Texas, the Gulf of Mexico, or near Cape Hatteras move northeastward and may pass close enough to Washington to deposit rain or snow. Polar air masses behind the associated cold fronts become generally moderate in temperature in their journey southward.

Significant microclimatological effects at Washington include the heat island associated with the densely built-up parts of the city, higher elevations north and west of the city, and the weak moderating influence of the Potomac River during summer.

Woolum (Ref 99) has summarized the distribution of temperature and precipitation as recorded at stations in the Washington Metropolitan Area Climatological Network. Average minimum temperature isotherms drawn for the Washington area for a 15 year period ending in 1960 show a significant heat island. This temperature anomaly is centered near the Potomac Yards south of National Airport with a maximum temperature of 49 degrees F compared to a minimum temperature of 44.5 degrees at Vier's Mill north of the city. Although the center of the heat island shifts with season, it is characteristically in the vicinity of National Airport, reflecting the distribution of built-up areas. Warmer temperatures also occur in a lobe extending northward beyond the urban center.

The profiles of maximum temperatures during daylight hours are unlike those for the minimum temperatures; some of this variability is probably induced by the local wind patterns. For example, the maximum temperature anomaly region for September becomes separated into two weak cells located east and west of the urban center. Thus the heat island over the airport region for the minimum-temperature profile is replaced by a more uniform temperature distribution with much wider separation of the isotherms. This would suggest the afternoon moderating influence of the Potomac. However, temperatures as much as 7 degrees F lower occur over the higher elevations north of the city near Vier's Mill.

Total annual precipitation in the metropolitan region is 41 inches. Locally the total varies by over 4.5 inches between the driest and wettest parts of the region. The least precipitation falls in the Potomac valley at its intersection with the Anacostia River valley; the maximum occurs at the higher elevations north of the district. Monthly totals are greater from May through September when winds are predominantly southerly. During the summer, the relatively cool water of the Potomac River stabilizes the air by local cooling from below, and shower activity is lessened. Orographic lifting of air over the higher elevations north of the city enhances shower development in that area.

Los Angeles

Los Angeles lies in the Southern California coastal plain with the Pacific Ocean to the west and south. The Los Angeles basin is bordered on the north by the San Gabriel Mountains, on the northwest by the Santa Monica Coastal Range, and on the east by the Puente Hills and the Santa Ana

Mountains. The Palos Verdes Hills on the south coast, although not extensive in area, do reach heights sufficient to exert a deflecting influence on local windflow. The maximum annual frequency of wind direction at Los Angeles International Airport is 37 per cent in the sector from West to WSW.

Air trajectories originating over the densely populated regions of the Los Angeles basin early in the day typically extend east of Pomona by afternoon and frequently reach Riverside and San Bernardino. A similar extension into the San Fernando Valley often occurs. The sheltering influence of the terrain and the persistence of low winds and atmospheric stability make this large population center an area of significant pollution occurrence.

Large-scale subsidence of air above the ocean-cooled surface layer is an important feature of the anti-cyclonic circulation around the Pacific high-pressure cell. The subsiding air is warmed adiabatically, providing a layer of warm air above the ocean-cooled surface layer. This stable stratification dominates in the area during the spring, summer, and fall.

During most days, a layer of cool marine air enters the coast as a sea breeze, arising because of strong heating over the land surface. Surface winds are characterized by a daily reversal in direction. On-shore winds occur during daylight hours, and the flow direction is reversed at night as cold air drainage from the surrounding mountains filters out to sea. The onset of the daytime and nighttime flow patterns lags sunrise and sunset by intervals varying up to a few hours depending on location.

The strength and depth of the on-shore sea breeze varies daily and the penetration of fresh marine air can often be distinguished by a measurable contrast in temperature and moisture content along the sea breeze front. Excepting days when fresh marine air penetrates deeply into the basin, the air beneath the subsidence inversion is usually advected back and forth across the region. This occurs because the large-scale atmospheric pressure gradient does not produce sufficient wind movement to carry air completely out of the basin. Thus, accumulation of pollutants in the same air frequently continues for a period of several days.

The inversion base height is also subject to daily oscillation. Along the coast, lowest heights occur in the late afternoon and early evening; inland locations experience lowest heights during early morning hours. These daily variations in inversion base heights cause significant changes in the severity of pollution within the marine layer of air.

These basic phenomena are complicated by local orographic features, by the existing large scale synopic patterns with their associated pressure gradients, and by fluctuations in the thermal trough over the adjacent continental area. Meteorological air trajectories have been summarized by time and season for this region by DeMarrais, Holzworth and Hosler (Ref 101). The California meteorological regime has received intensive investigation (Refs 92, 102, 103, 104, 105, 106, 107, 108, and 109).

In addition to unfavorable ventilation conditions, the Los Angeles Basin exhibits other features essential to photochemical pollution. These include strong sunlight, generally clear skies, and reactive emissions from dense population centers. Various long-term projects have involved measurement and analysis of photochemical reactants and by-products within the Los Angeles Basin. Trends, seasonal and diurnal variations, and geographic variability related to land-population usages have been investigated.

Pertinent treatments have been published by various authors (Refs 110, 111 and 112).

Aircraft Operational Procedures

Fuel consumption rates, the duration of emission, the species of the contaminant emitted, and the altitude of release are determined largely by the aircraft operating cycle and by variations in flight procedures due to unusual circumstances. These factors can be described by following a typical turbine-engine aircraft operating cycle from engine start-up to shut-down at destination.

(1) Engine Start-up - A quantity of raw fuel due to the start-up procedure is released from the exhaust nozzle. Because of incomplete combustion, high concentrations of hydrocarbons, carbon monoxide, and particulates are released during this procedure. Significant engine and combustion noises also accompany this operation. After start-up, the engine operates in the idle condition which produces the highest carbon monoxide and hydrocarbon emission rates.

(2) Aircraft Departure from Terminal Gate - The jet exhaust products are generally directed toward the terminal as the aircraft turns to leave the loading area. The aircraft may be required to wait on the terminal apron with engines at idle condition before proceeding.

(3) Taxi - The engines operate under idle conditions during most of the taxi mode. The duration of the aircraft taxi period depends on the distance from the terminal ramp to the end of the runway. The taxi speed is determined by the proximity of

parked and moving aircraft. The holding time at the end of the taxi period is a function of the time required for take-off and the number of aircraft awaiting departure. When a line of aircraft forms on the taxi strip, emissions are generally directed along the line into the paths of the aircraft at the rear of the line. During unfavorable weather conditions, or during other operational difficulties, hold-times may exceed one hour.

(4) Take-Off - The ground run for take-off occurs under maximum engine power conditions and at the maximum fuel consumption rate. Exhaust temperature and velocity are highest under this maximum power condition.

(5) Climb-Out and Noise-Abatement Procedure - The first segment of climb-out occurs at maximum power up to the altitude specified by noise abatement procedures. For example, at Washington the procedure requires a climb to 1500 feet, at which point power is reduced to an engine setting computed for hot-day conditions at maximum gross take-off weight to give approximately a climb rate of 500 fpm. This reduced power is maintained until the aircraft is approximately 10 miles from the terminal. The power reduction results in emissions at lower altitudes for longer times over the metropolitan area; however, emissions rates are also lower.

(6) Holding Prior to Proceeding on Course to Destination - Holding while awaiting instructions to proceed on course generally occurs within a 10-mile radius of the airport at an altitude

of a few thousand feet. The engine operates at cruise power conditions during this time.

(7) Cruise - The aircraft cruises above 27,000 feet at a cruise power setting. Engine efficiency is high and emission rates for CO and hydrocarbons are minimal.

(8) Let-Down and Approach - The aircraft reduces altitude to a certain geographical position prescribed for approach to the airport. For Washington National Airport, the aircraft is at 3000 ft when 10 nautical miles away, 2100 ft at 7 miles, 1500 ft at 5 miles, and 900 ft at 3 miles. Thus the aircraft is usually well within the mixing layer while over the metropolitan area. Engine power during approach is 40 to 60 per cent of maximum power. If weather or operational difficulties require the aircraft to hold before making the approach to the field, the holding patterns are at higher altitudes and usually outside of the 10-mile radius from the airport.

(9) Missed Approach Procedure - An aircraft missing its landing approach proceeds to a special radial fix and holds at that fix while awaiting further instructions. For example, at Washington the aircraft climbs to 2000 feet and holds at the Washington, D. C. radio beacon. At Los Angeles, it climbs to 3000 feet and holds at Kingfish intersection (over the ocean) until directed to start another approach. Maximum power engine operation is employed during the climb to the holding altitude, and cruise power is used in the holding pattern.

(10) Landing - After touch-down the engine power settings are at idle until thrust reversal, when high power is applied until a safe taxi speed is realized.

(11) Taxi - Engine conditions are at idle. Delays are encountered if taxi strips or the parking area are fully occupied due to an overload at the terminal area.

(12) Shut-Down - Some raw fuel and odors are emitted momentarily during the shut-down procedure.

Aircraft Flight Patterns

The horizontal spreading and the vertical angle of flight paths reduce the impact of aircraft engine emissions occurring in flight below that inferred from comparisons of emission totals and contamination per unit of path length for ground and flight operations. In comparison to flight operations, ground operations are confined to a fixed (and relatively small) area.

Major differences among flight patterns exist for the various terminals. At J. F. Kennedy, flight operations are distributed in four major directions. Forty per cent of all operations employ the most heavily used sector, the northwest, and nine per cent employ the least used, northeast sector. Take-offs to the northwest are constrained by noise abatement procedures.

There also are constraints imposed on flight paths by noise abatement at Washington National Airport. Both landing and departing aircraft are required to follow closely one of the major rivers; thus very little horizontal spreading of emissions during flight operations can result from variation in flight paths.

In Los Angeles at least 95 per cent of all take-offs proceed seaward (west), and a like percentage of landing aircraft approach the terminal from the city (east). Over 40 per cent of all landing operations at Los Angeles follow a westerly glide path which begins 15 or more miles east of the airport near Whittier. A similar percentage enters this glide path from the north, and the rest from the south, at distances between 3 and 10 miles from the terminal. Thus almost all of the landing operations at Los Angeles pass over a zone to the east of the terminal which is not more than about 1 mile wide.

Number of Flights and Classification of Aircraft

The total number of aircraft operations and the types of aircraft determine the amount of the aircraft exhaust emissions in the vicinity of each airport. Aircraft operations on the ground produce the greatest amount of contaminants, and these contaminants are distributed within the passenger terminal area, on the aircraft ramp and taxi strips, along runways and into the areas surrounding the airport.

Aircraft activity have been tabulated by frequency and classification earlier in this report. A simplified aircraft operational cycle described in Table 2, was used to estimate the relative importance of aircraft engine emission in total community air pollution. Estimates of total emissions at five major air terminals, in three metropolitan areas, and over the entire nation are summarized in Table 48.

Diurnal Variation of Aircraft Activity and Meteorological Factors

A diurnal variation of air quality results from the variation of all emission sources and the variation of the ventilation rate of the local atmosphere. For area-source and transport phenomena, the ventilation rate for the atmosphere can be expressed as the product of the local mixing layer depth and the wind speed within this layer.

In general, aircraft activity begins with the onset of daylight hours, increases during the day, continuing well into the afternoon, and decreases thereafter. This behavior is typical of most man-related activities; hence other source activity follows a similar pattern.

The diurnal variation of air pollution potential has been investigated by Holzworth (Refs 113 and 114), who has prepared monthly mean mixing depths and average wind speeds from morning and afternoon upper-air soundings at various locations. The monthly mean ventilation rates for New York, Washington, and Los Angeles are shown in Figure 16. Based on this long-term climatological data, the diurnal range of ventilation rate is greatest for Washington and least for Los Angeles. The diurnal range for New York is intermediate.

Vertical mixing in the lower layers is suppressed during stable atmospheric conditions such as during early morning inversions and subsidence and frontal inversions. The height of the mixing layer increases during the afternoon as a result of solar heating. During cloudy and windy days, the diluting power of the atmosphere changes less, and variations in air quality are more closely related to diurnal variations in the source emission rates.

Local Impact of Aircraft Emissions

An Area-Source Model for Pollutant Concentrations Near Airport Boundaries

Concentrations reaching nearby receptors downwind from the edge of an airport may be estimated by an airport area-source model. Emissions caused by low altitude operations from idle to lift-off (but not climb-out) are assumed to constitute a surface of randomly distributed multiple sources. For a first approximation, this surface is considered as a uniform area source with respect to a receptor located 100 meters downwind from the airport edge for sampling times exceeding the temporal variations of emission strength. The area of the airport includes the loading area, taxi strips and runways; the area is configured as a rectangle with one side facing the prevailing wind.

Each infinitesimal strip of the area normal to the wind direction is an effective line source. Integration of the concentration received from all strips, starting from the windward edge of the airport to the downwind edge just short of the receptor, provides a relationship for the concentration at the receptor due to the area source.

For the infinitesimal strip, the line source formula (Ref 115) is

$$d\,X\,(s) = -\frac{2}{\sqrt{2\pi}}\;\frac{Q}{u}\;\frac{ds}{\sigma_z}$$

and the integral for a receptor 100 meters from the downwind edge becomes

$$X = \frac{2}{\sqrt{2\pi}}\;\frac{Q}{u}\int_{100}^{100+L}\frac{ds}{\sigma_z}$$

where X is the concentration, Q is the strength of the area source (rate of mass emission per unit area), u is the wind speed, s is the distance of the receptor from any infinitesimal strip source, σ_z is the standard deviation of the plume along the vertical (a function of travel distance from the strip to receptor), and L is the along-wind dimension of the airport.

In the range of travel distances appropriate to the airport model (100 to 5,000 meters), the vertical plume dispersion statistics reported by Slade (Ref 115) may be approximated by

$\sigma_z = 0.158\ s^{3/4}$ (meter) for the neutral stability category (D) and

$\sigma_z = 0.06\ s^{3/4}$ (meter) for the stable category (F).

The resulting expression is

$$X = \frac{8}{\sqrt{2\pi}}\ \frac{Q}{au}\left[(100+L)^{\frac{1}{4}} - 100^{\frac{1}{4}}\right] ,$$

where "a" is the appropriate numerical coefficient from the expression for σ_z (either 0.158 or 0.06).

This relationship has been applied to John F. Kennedy, Washington National and Los Angeles International Airports, with an assumed wind speed of 5 miles per hour (2.2 meters per second) and with downwind dimensions of 4000, 2400 and 4000 meters respectively. Emission densities calculated for average busy hours (10 am to 10 pm) have been used; these estimates, and the airport area data used in developing the estimates, are summarized in Table 57. Emissions during the climb-out and approach modes of aircraft operation have been excluded because the model treats surface level emissions only. This exclusion is not a serious limitation for the calculation of concentrations very near the airport boundary. The choice of wind speed (5 miles / hour) is arbitrary; it provides a uniform basis for comparison of of airport size and emission levels.

Table 58 summarizes the concentrations calculated for the three airports and for the two stability categories. The effect of atmospheric stability is evident: predicted concentrations differ by a factor of approximately 2.5 between the neutral and stable cases. Predicted CO concentrations exhibit the greatest variability, having a maximum for Washington during stable conditions. Long-term average concentrations of certain pollutants in the Washington and Los Angeles Areas also are listed in the table for comparison with the calculated values for air terminals.

With the assumed dispersion conditions, the model predicts contaminant concentrations near airports which represent detectable changes in expected average concentration in urban areas and which are greater than the sensitivity of the detection methods normally employed. Consideration of predicted concentrations should be an integral part of the planning for preservation of environmental quality in the vicinity of proposed new or expanded facilities and of the development of programs to improve environmental quality near existing facilities.

Under certain conditions small groups of receptors can be exposed in a manner not represented by the area source model. There are a number of major air terminals at which residential areas are located along an extension of a runway or within a mile or less of the end of the runway. When the runway is in use the wind is generally parallel to the runway axis and directed toward the neighboring area. Residents of such an area may experience concentrations significantly higher than those predicted by the area source model.

Field studies of air quality conducted to date have not been directed toward the evaluation of a specific condition or the validation of any prediction model (Refs 118, 119, and 120). Their findings support a general conclusion that aircraft engine emissions are presently of minor importance to metropolitan areas or to specific communities, but they did not attempt an evaluation of localized impact, either on the residents of areas near an airport or on travelers and employees within the terminal area. A considerable quantity of data is available on air quality from sampling stations in Los Angeles County, operated by the Los Angeles Air Pollution Control District, including a station (Inglewood - Sta. 76) located east (generally downwind) and within about 1/2 mile of Los Angeles International Airport. A detailed evaluation of this data, together with operational data for the airport, is suggested as a future task. At this time we are unable to report that observations of air quality in the vicinity of major airports show positive evidence of deterioration due to aircraft engine emissions, even though we predict that such changes might be observed.

Impact Within the Airport Neighborhood

An extension of the area-source model, for the meteorological and source conditions assumed, from 100 meters downwind to 1000 meters downwind of the air terminals considered, results in the prediction of concentrations approximately one-half of those indicated in Table 58. These estimates represent a conservative upper range for concentrations 1000 meters downwind from the three subject airports. The area source model assumes constant emission density along infinite cross-wind strips, and the finite lateral dimensions of the airports cannot be considered as "approximately infinite" for downwind distances as large as one kilometer. Consequently, actual concentrations at these distances will be less than the concentrations predicted by the area-source model. Thus it seems unlikely that any measurable impact of aircraft engine emissions will be detected at these distances (Refs 121 and 122). Improvement and validation of these predictions would require the design and conduct of a special study to acquire and relate concurrent values for aircraft operations, micrometeorological variables, and ambient concentrations for a selected contaminant or a suitable tracer at several points.

Many authors cite "visible emissions" from aircraft engines as a major cause of concern. Our evaluation of complaints by residents of areas near Kennedy Airport and another major jetport (See Appendix III) indicates a general adverse reaction by this group to "air pollution". This may be due in part to obscuration of the observer's low-angle background, an effect readily seen during peak operating periods. We have little data to quantify such an impact, and it is our opinion that while it is probably real, it is of minor importance in comparison to the impact of aircraft noise on these same observers.

Occasional complaints cite, in part, annoyance due to odors, or due to soot or oil drops settling on property. We are aware of no field data in support of this alleged particulate problem. Nolan (Ref 119) has pointed out that the particles emitted from aircraft engines are quite similar in nature to those emitted from other mobile combustion sources. Further evaluation of this matter should be undertaken. Although Nolan was unable to define a community odor problem in his limited study around JFK Airport, and although our review of complaints of air pollution attributed to jet aircraft does not demonstrate such a problem, it is difficult to reject the hypothesis that the characteristic odor of jet engine emissions is sometimes detected in the neighborhoods around major air terminals.

Jet noise and, perhaps, fears associated with low-altitude overflights have greater impact on the population than air pollution near major terminals. This is supported by complaint data, newspaper files, interviews, and by consideration of past and proposed legislative and legal actions. Effective actions to reduce exposures of resident populations to aircraft noise will also generally reduce the exposure of these same populations to air contaminants emitted by aircraft.

Pollutant Concentration Variations Within Airports

The preliminary model described above gives no indication of the spatial and temporal variations in concentration levels within or near an airport facility. Contaminant levels at ground and at altitude, and their relationship to the mode of activity: idling, taxi, take-off, climb-out, approach and landing, could be estimated by appropriate models of each activity.

Within terminal areas, in comparison to neighborhoods, different modes of exposure, different populations, and higher concentrations of contaminants must be considered. The exposed population consists of (1) transient passengers and visitors, (2) persons such as taxi drivers, pilots and flight crews, who repeatedly pass through the area, and (3) airline, terminal, and governmental employees assigned to duty in the terminal area. In the first and second cases, the exposure is sporadic. In the third case and possibly the second case, an occupational exposure is involved. The implications of the exposure differ because of the people exposed and because of their required activities.

Visible aircraft engine emissions have not been shown to be of concern to this population. The dearth of data reflects the absence of attempts at evaluation, and may also reflect the lack of effective systems to receive and record indications of impact. This population should not be particularly aware of visible emissions which occur during airborne phases, take-off, and thrust reversal on landing, but are not associated with operations near the passenger facilities.

Emissions of odorous material, or of particulates in the forms of soot, other solids, or liquid drops, might be expected to affect employees or transients in the immediate terminal area. Even though aircraft engine emissions are known to exhibit a characteristic odor which is frequently detectable in these areas, no evidence of expression of concern with odors on the part of this population was obtained. This may again be due to the absence of a readily available system for registering such concern, but is also probably attributable to motivation or attitude. Furthermore, terminal enclosures at some major airports employ air-conditioning systems which substantially reduce concentration of odorous material in intake air. Some oral reports of deposits on cars left in terminal areas have been received, but no field studies or complaint records are available to support these reports.

Human exposure in terminal areas is either occupational in nature, or quite brief and occasional. In either instance no significant adverse effects on well-being are suggested by the predicted concentrations of air contaminants in these areas. Greater exposures could occur during some conditions, and a more detailed consideration of concentrations in terminal areas, and of public and employee response to these exposures, is indicated.

Attempts to calculate concentrations of contaminants expected within terminal areas are hindered by the variable configurations of buildings and open spaces within these areas. Sample calculations for the case of a four engine turbine aircraft moving slowly away from a terminal building result in predicted concentrations which are no higher than those summarized in Table 58. Repeated fumigation of partially or totally enclosed areas (possibly caused by frequent aircraft departures from the same gate, for example) might result in the build-up of significant concentrations, and it would be worthwhile to sample contaminant levels in a few such high-risk areas at the major airports.

More refined estimates of concentrations within air terminal areas await quantitative descriptions of the initial mixing of engine exhausts with the ambient atmosphere. Qualitatively, the engine exhaust trail may be considered as being composed of the jet phase and the plume phase. The jet phase is described by those characteristics of momentum, heat and buoyancy that are determined by aircraft engine combustion, while the plume phase is governed primarily by the ambient atmospheric environment. Analysis of the jet and plume require knowledge of the rate at which momentum and buoyancy are reduced by mixing with the surrounding atmosphere as well as the atmospheric diffusion process. Aircraft control structures, such as flaps, and the aerodynamics of wing-tip vortices, also modify the jet plume.

At some point in the engine exhaust trail, the characteristics of the plume are determined entirely by atmospheric diffusion. The lateral and vertical plume dimensions at this point might be obtained either by measurement, or by calculation from known heat and momentum characteristics of the jet phase where the jet velocity goes to zero and the temperature becomes ambient. For purposes of estimating concentrations at points farther downwind, it is useful to consider the plume as having originated from a virtual point source ahead of the aircraft. The extrapolation to the virtual source is predicated on the dispersion characteristics of the downwind plume. Travel distances downwind are referred to the virtual point source in subsequent estimates of pollutant concentration. Methods of determining virtual source location in the case of aircraft emissions have not been specified. Plumes from aircraft in motion present a class of diffusion problems not usually encountered in the diffusion meteorology of stationary sources.

A stationary aircraft emitting at idle setting approximates the continuous point source model used in estimates of industrial stack emission. Aircraft moving at speeds much greater than the wind may be approximated by a model designed for the analysis of instantaneous line sources. Between these two extremes, during the taxi mode, the combined effect of aircraft and wind motion may significantly alter the dispersion. For example, a strong headwind acting on an aircraft in taxi will dilute the emissions at a rate exceeding the no-wind condition. A tail-wind comparable in magnitude to the forward speed of the aircraft will ultimately reverse the direction of the effluents and act to collect them in a cloud moving with the plane.

Describing the development of an aircraft engine exhaust plume by means of a quantitative model is a necessary step toward assessment of pollutant concentrations within terminal areas. This task is recommended as a subject for future research.

Aircraft Cabin Exposures

During taxiing, idling, and even during take-off, an aircraft may be directly exposed to the exhaust of a preceding craft. The diluted exhaust can be drawn into the airplane through its ventilating system, exposing both crew and passengers to contamination. The obvious manifestation of this exposure is an odor of exhaust fumes. In order to assess the potential hazard to either crew or passengers in this event, calculations of contaminant concentrations in the wake of taxiing aircraft were carried out and are summarized in Figure 17. Estimates of wake volume were based on field observations of the near-instantaneous expansion of visible emissions during take-off. For limited exposures, no hazard is indicated by the concentrations predicted. However, several aircraft frequently are aligned behind one another awaiting take-off clearance at the major air terminals, and total hold time during periods of peak activity is sometimes of the order of an hour. It would be desirable to carry out a program of sampling for CO within typical aircraft cabins, and particularly within the crew compartments, during such multiple-source exposure conditions.

Except for some concern in the past over visibility reduction on the runway during multiple take-offs of military aircraft using turbojet engines with water-injection (Ref 123), we found no references to operational problems created by visible emissions. In fact, one verbal report was received from a pilot of small, air taxi aircraft that turbulent exhaust plumes from large turbine-engine aircraft are easier to avoid when they are visible.

Relative Importance of Aircraft Emissions in Total Community Air Pollution

Importance of Operations and of Operating Modes

A distinction between aircraft operations on the ground and aloft should be made, and a distinction between types of aircraft drawn. In this way the relative importance of various aircraft and operating modes can be established, and the possibilities for improvement can be ranked. Aircraft classes and operating modes are summarized in Tables 1 and 2, and Table 48 illustrates 1967 daily average emission rates for CO, hydrocarbons, NO_x and particulates by all aircraft operating within the three major metropolitan areas considered in this report.

Tables 44 through 47 further illustrate the relative importance of certain classes of aircraft and modes of operation to total emissions of air contaminants by aircraft engines below 3000 ft in metropolitan areas. In regions with a preponderance of jet traffic (New York and Los Angeles), ground-level emissions of CO and hydrocarbons are substantially greater than emissions aloft. This is due principally to emissions of CO from taxiing jets. Where piston-engine traffic dominates (on a national basis and in Washington, for example), emissions of these contaminants by aircraft during flight are greater. In New York and Washington the phasing out of large piston-engine aircraft (Class 5) would largely eliminate emissions aloft of CO, but much greater numbers of small (Class 6) aircraft will probably be operated in the future. In Washington, and nationally, phasing out of Class 5 aircraft will have a similar effect on total hydrocarbon emissions aloft. At major jetports handling Class 1 aircraft (Kennedy, Los Angeles), emissions of CO and hydrocarbons from aircraft operating on the ground are far in excess of emissions during approach and climb-out.

Operations associated with these two terminals are responsible for about half of total contamination from aircraft in the respective metropolitan areas (Table 48). Washington National is slightly less important for aircraft-caused contamination in its metropolitan area. In each instance operations at the major jetport result in less than half (about 40%) of total CO emissions from aircraft in their respective metropolitan areas.

For a further evaluation of the relative significance of emissions during ground and flight operations it is interesting to compare emissions per unit of path length, thus indicating the potential for contamination of different air masses. Table 2 illustrates assumed landing and take-off patterns for all aircraft types, giving path lengths, average velocities, and elapsed times. Emissions per unit of path length have been computed for the paths illustrated, and the results are presented in Table 59. Taxi distances differ among airports and within airports on the basis of the origin or destination of the aircraft, and because of the runway in use. Further, the speed of taxiing may vary because of congestion or the nature of the path. Thus, a "typical" emission per unit of path length based on a taxi speed of 15 mph, is computed for the taxi mode, using emission rates previously stated. Two aircraft classes were selected to illustrate the range of contaminant "linear concentrations" that are produced. In general, ground operations cause substantially greater instantaneous concentrations of pollutants in the aircraft wake. Since ground operations also provide greater opportunity for multiple injections of contaminants into the same air mass, it is expected that contaminant concentrations in and near aircraft wakes will be greater for wakes or plumes resulting from ground operations. Predictions of actual concentrations are not made because the initial expansion of the exhaust jet has not been established.

Relationship Between Aircraft Emissions and Emissions from Other Sources

Lemke et al (Ref 3) for Los Angeles County, Nolan (Ref 119) for J. F. Kennedy Airport, Hochheiser and Lozano (Ref 120) for the New York metropolitan area, and Johnson and Flynn (Ref 124) for the San Francisco Bay area, have calculated total emissions of several contaminants from aircraft engines and have compared these to emissions from other sources in the respective areas. Such values and comparisons are germaine to considerations of the relative importance of these emissions to problems of photochemical smog and atmospheric turbidity in the areas represented. Aircraft engine emissions are not uniformly distributed, however, in either the horizontal or the vertical. Nolan and subsequently Hochheiser and Lozano also expressed emissions as a function of the land area of the terminal from, to, or at which the activity occurred, but assigned the total of emissions from all operations below an altitude of 3,500 feet, to the terminal area. We suggest as a further extension of this approach that the terminal area be approximated as an area source whose strength is due to aircraft (and other) operations on the ground, and that operations aloft be considered as distributed more generally throughout the metropolitan area. "Ground operations" of aircraft include taxi, idle, take-off and landing rolls, and run-up and other maintenance operations. (Evaporative and displacement losses from fueling, motor vehicle emissions within the terminal area, and emissions from housekeeping activities such as generation of power and heat and cooking should be included also.) This permits a comparison of the terminal area to its immediate surroundings, as well as a comparison of emissions from aircraft engines to totals of emissions in metropolitan areas or selected portions. "Terminal area" is defined here as the portion of the land area of the airport used for aircraft operations, and includes runways, taxiways, aircraft gate and parking areas, and surrounding land not otherwise used. It excludes that portion of the airport land area used for motor vehicles, fuel storage, passenger and freight facilities, other non-aircraft operations, and that occupied by buildings of all types. Emissions of contaminants (from engines of aircraft during ground operations) expressed as "emission densities" ($MT^{-1} L^{-2}$) are compared to emissions, similarly expressed, of those contaminants from sources within nearby areas beyond the airport boundaries. These comparisons are made in Table 60 for J. F. Kennedy International, Washington National, and Los Angeles International airports. Emission densities in the terminal areas are, of course, greater than they would be if the areas were unused. However, Table 60 shows that most emissions are less than they would be if presently adjoining types and degrees of land use had occupied the areas.

Table 53 shows the relationship between present average activity and peak activity at major terminals, and illustrates the potential for increases in emissions. Such activity and the concommitant emission increases, if realized, could result in carbon monoxide and hydrocarbon emission densities within the terminals which would be as great or greater than present emission densities in areas adjoining and near to the terminals. In turn, air quality (as influenced by CO and hydrocarbon concentrations, and possibly by the products of photochemical reactions) in and near the terminals would deteriorate, perhaps to a lower level than is now found in the adjoining areas.

It should be noted that the emission densities shown in Table 60 for regions near terminals are averages for the region. Large variations exist, of course, and are illustrated in Table 61. (The data are derived from the same sources as used in Table 60.)

It is of interest to compare the sum of all contaminant emissions from aircraft engines to those from other source categories, within a time period of interest and within a metropolitan air mass. Table 62 presents such comparisons, for Los Angeles, New York, and Washington, with respect to carbon monoxide, hydrocarbons, oxides of nitrogen, and particulates. This table shows that air contaminant emissions from aircraft engines are a small fraction of the sum of such emissions from surface transportation sources, and are of even less significance with respect to emissions from all sources, in the metropolitan areas considered. There is no reason to assume that circumstances would greatly differ in any major urban center in any technologically advanced country. Generally, greater opportunity exists for dilution and dispersion of emissions from moving airborne sources, as compared to stationary or moving sources at the ground prior to exposure of any receptor. Substantial fractions of aircraft engine emissions occur aloft in the areas studies (CO, one/third; hydrocarbons, one/third; oxides of nitrogen, one-half; particulates, two/thirds; all ratios approximate). Therefore, except for photochemical, condensation, and light-scattering processes, aircraft emissions are of even less significance than the percentages shown in Table 62 would indicate.

The importance of reciprocating engine (piston) aircraft emission for local and community air pollution in comparison to jet engine emission, and in comparison to other sources deserves note. Aircraft powered by reciprocating engines emit a substantial portion of the total contaminatin produced (viz., over 50 per cent of the total carbon monoxide discharged annually by aircraft in the New York metropolitan area, and all of the lead discharged by aircraft); however, these emissions are accompanied by less noise and less smoke than the emissions from turbine engines. Lead discharged by piston aircraft engines, while constituting all of the lead attributable to aircraft operations (11,000 tons per year), is only 6 per cent of the 190,000 tons of lead discharged each year from motor vehicles (Ref 125). Most (70 per cent) of the lead from aircraft is discharged during flight and is therefore more widely distributed than is lead discharged from motor vehicles. Carbon monoxide from piston aircraft engines represents about 80 per cent of the total CO from aircraft operations within metropolitan areas. However, total CO emissions from aircraft are not significant in comparison to CO emissions from motor vehicles. Further, CO from piston engine aircraft is largely (over 65 per cent) discharged during flight.

CO emissions were considered for two major "light aircraft" facilities, Long Beach Municipal Airport in Los Angeles County, and Teterboro Airport (PNYA) in New Jersey (N.Y. Area). Total carbon monoxide emissions at those facilities were, respectively, 15 per cent and 6 per cent of the corresponding values for major terminals in the area (LAX or JFK) in 1967. Therefore operations at airports of the Long Beach or Teterboro type are not presently considered of importance in influencing community carbon monoxide levels. The growth potential at these facilities is large, however.

Future Trends

It is clear that increases in aircraft activity and other factors will bring about increases in aircraft emissions in future years. At the same time, emissions from other sources are expected to be reduced substantially as a result of control measures. Current emission rates from automobiles and aircraft in Los Angeles County are shown below along with rates anticipated in the next 12 years (Ref 117):

Pollutant Emissions from Automobiles and Aircraft in Los Angeles County - 1000 lb/day

Year	Source	CO	Organics	NO_x
1967	Automobiles	22,000	4,700	1,040
1967	Aircraft	170	39	6
1979	Uncontrolled Automobiles	30,400	6,500	1,430
1979	Controlled Automobiles	9,900	1,200	2,200
1979	Uncontrolled Aircraft	270	71	26

These projections indicate that the contributions by aircraft to total emissions of CO and organics in Los Angeles County will increase from current levels of less than 1 per cent to 3 to 6 per cent over a ten year period.

Sensory Effects (Smoke)

Certain emissions from aircraft engines are not regarded as hazardous to health, but do produce adverse sensory effects. Such emissions can be regarded as having an esthetic impact. Aircraft emissions in this category include visible or smoky exhaust plumes. Emission of smoke by turbine-engine aircraft has an impact upon the populace beyond its contribution to local and community particulate concentrations. The quantity of solid material in an aircraft exhaust plume is surprisingly small. During its climb-out mode, the plume from a 3-engine, medium-range, jet transport is estimated to contain 0.2 pounds of carbon per mile of travel. But, because of the physical characteristics of this material, it is highly visible even at this low density. The impact of smoke trails, therefore, must be regarded as sensory or esthetic. Nevertheless, smoke must be taken seriously since it is a source of criticism from the public. The fact that its impact has been registered with the aircraft industry is evident from reports of efforts by engine manufacturers to eliminate smoke trails.

Interactions Between Aircraft Safety, Noise, and Pollutant Emission

There are three aspects of aircraft operations which are of concern to the public and to government regulatory agencies. These are safety, noise, and pollutant emission. Pollutant emission, at the present time, is of less concern than the other factors. Consequently, interactions between pollutant emission, approaches to emission control, noise generation, and safety should be identified to assure that emission control measures are not proposed which would aggravate other problems.

Aircraft engines produce very high noise levels as well as pollutants. In the past, most attention has been given to reducing the impact of engine noise upon surrounding areas. It would, therefore, be undesirable to reduce pollutant emissions using methods that would increase engine noise. Fortunately, the rate of pollutant emission for a given engine at a constant thrust setting is not related to the noise generated. Therefore, changes to the combustion chamber aimed at reducing emissions will not influence the noise emitted. The only interaction between noise and pollution arises from the need to reduce thrust settings during climb-out from airfields to comply with local noise abatement procedures. This reduction in thrust will reduce the rate of pollutant emissions, but will increase the time spent in climbing to 3000 feet. The percentage changes in emission rates and climb-out times are small, and the resulting changes in the total quantities of pollutant emitted, when satisfying local noise abatement requirements, are negligible.

Safety considerations receive the highest priority whenever changes in aircraft operations or equipment are contemplated. Any modification of engines to reduce pollutant emission must not reduce the reliability of engine operation during flight.

Smoke emission from turbine engines is of concern, particularly during flight operations, and three approaches to smoke-reduction have been considered. The safety aspects of these approaches are as follows:

1. Changes in combustor design could impair inflight engine relight capability (ability to start an engine while in flight).
2. Fuel additives could impair the performance and reliability of the engine over long periods of operation.
3. The use of non-hydrocarbon fuels (e.g., hydrogen) constitutes a greater fire hazard than the use of current aviation fuels.

At the present time only combustor design modifications are thought to be a practical approach to emission reduction. It is now accepted that low-smoke combustors can be designed without a significant penalty on performance or altitude relight capability (Ref 129).

Gaseous pollutants from turbine engines are of concern primarily during ground operations. Recommended approaches to reducing these emissions include improved combustor performance at low power settings and curtailment of ground operations. These approaches are not likely to affect the safety of flight operations.

With regard to piston engines, certain approaches to emission reduction are considered to be impractical as they would degrade engine performance. However, exhaust gas treatment, which has been proven to be effective in automobile engines, should be equally applicable to aircraft engines, without affecting performance or safety.

There are two other possible interactions between pollutants emissions and safety:

1. Excessive smoke emissions could reduce visibility at the end of runways. At this time, reduction in visibility due to aircraft engine smoke is small, and the resulting effect upon the safety of aircraft is negligible.
2. Excessive CO and NO_x levels near stationary aircraft could result in high concentrations of these pollutants in the aircraft cabin which could impair the performance of the flight crew. At this time these levels are not thought to be high enough to constitute a hazard, but this potential hazard should be kept in mind in the future.

In general, it appears that interactions between pollutant emission, noise, and safety are minor, and that certain approaches to emission reduction can be introduced without increasing noise or impairing safety. In fact, in some circumstances, reduced emissions may improve the safety of aircraft operations.

Summary

At the present time, two aspects or categories of impact of air pollutants are recognized. The first of these is the exposure of persons or property to concentrations of pollutants which could cause injury or discomfort. The second aspect is the degradation of the atmospheric environment. Whereas the first aspect is concerned with the health of persons and the maintenance of their property, the second is concerned with esthetic values associated with life in an urban community. Aircraft emissions, like pollutants from other sources, are of concern from both standpoints.

Aircraft emissions having the greatest impact are those released during air terminal operations because of the concentrations of aircraft activity and the fact that this activity occurs largely at ground level. Because of this concentration of activity at air terminals, emissions from aircraft have local effects which differ from their effects on the over-all community.

Local Impact

In assessing local impact of aircraft emissions, we are concerned with the exposure of persons or property to high concentrations of pollutants as a direct result of aircraft activity. Persons most likely to be affected include airline or air terminal employees, airline crews and passengers, and residents of areas adjacent to air terminals. These persons are exposed to atmospheric concentrations of pollutants resulting from the combined effects of aircraft operations and the operation of other pollutant sources in the community. If the concentrations of aircraft emissions are higher or lower than concentrations of pollutants from other sources, the impact of these emissions can be said to be higher or lower than the impact of other pollutants.

Present Magnitudes

Field studies of air quality have been conducted in urban areas, including air terminal vicinities. These studies have not revealed the presence of unusually high pollutant concentrations near air terminals. This evidence, though limited, has led to the conclusion that hazardous concentrations of pollutants do not exist generally throughout air terminal areas. There are, however, circumstances where persons might be exposed to pollutant levels well above average levels due to concentrations of aircraft activity, and these circumstances have not been investigated by field test. Of greatest concern is the concentration of emissions resulting from aircraft take-off operations. The combination of aircraft waiting with engines idling and others beginning their take-off runs at low velocity and with engines at full throttle undoubtedly results in above average pollutant levels near the runway. Exposure of aircraft crew members, passengers, and residents of neighboring areas to emissions from these operations is a subject yet to be investigated. Similarly, concentration of emission sources occurs in the passenger loading areas. Here aircraft emissions are combined with emissions from other sources including auxiliary power units and automobiles passing through the terminal area.

If pollutant concentrations at air terminals are similar to those in surrounding communities, as is indicated by field measurements, the impact of aircraft emissions cannot be determined directly because they cannot be distinguished from pollutants from other sources. Aircraft emissions contain essentially the same pollutant ingredients as automobile exhaust gases. The impact of aircraft emissions can be assessed, however, by comparing the density of emissions at air terminals with emission densities in surrounding communities. Such a comparison is shown in Table 60. With few exceptions, this comparison indicates that the densities of emissions at air terminals from aircraft alone are comparable to densities of emissions from other sources in adjacent communities.

Another basis for comparing the impact of aircraft emissions with those from other sources is provided by calculating pollutant concentrations at air terminals resulting from aircraft operations. Such a calculation requires a knowledge of pollutant emission rates and an understanding of meteorological dispersion mechanisms. Calculated levels of pollutant concentrations are shown in Table 58 for busy hour activity levels and two different meteorological conditions. These are compared with average community concentrations where these data are available. Comparisons indicate, where they can be made, that pollutant concentrations from aircraft at air terminals are approximately of the same magnitude as average concentrations from other sources in metropolitan areas. On this basis, it is concluded that the local impact of aircraft emissions is comparable to the impact of emissions from other sources.

Also included in Table 58 are recommended limits on atmospheric concentrations of pollutants in urban areas. These limits represent current opinions on pollutant levels which have impact on either the health or esthetic values of the populace. It is evident that local concentrations of certain pollutants resulting from aircraft activity are comparable to these recommended limit values.

Future Trends

In future years, quantities of pollutants emitted by aircraft are expected to increase if no emission controls are adopted. Concentrations of these pollutants in air terminal vicinities will increase proportionately. During the next ten years, concentrations of CO, organics, and particulates are expected to increase by 50 to 100 per cent, and NO_x concentrations will increase by a greater amount. Consequently, the impact of these emissions on persons in air terminal vicinities, though perhaps marginal today, will become serious in the future.

Community Impact

Aircraft exhaust emissions released during ground operations at air terminals and during low-altitude flight operations over a community mix with emissions from other sources in the community and contribute to "background" concentrations of atmospheric pollutants. These background concentrations vary with over-all emission rates and with rates of atmospheric "ventilation" determined by meteorological and geographical factors.

Present Magnitude

Aircraft emissions cannot be distinguished from emissions from other sources when all are mixed together in the community atmosphere. Consequently, the relative contribution by aircraft can be determined only by comparing estimates of emission rates from aircraft with rates from other sources. Such a comparison is shown in Table 62 for three metropolitan areas. On the basis of estimates of aircraft emissions made during this study and estimates of emissions from all sources made by other investigators, aircraft emissions constitute between 0.2 per cent and 2.3 per cent of all CO, organic, NO_x, and particulate emission in the areas considered.

Future Trends

It is clear that increases in aircraft activity and other factors will bring about increases in aircraft emissions in future years. At the same time, emissions from other sources are expected to be reduced substantially as a result of control measures. Future projections indicate that the contributions by aircraft to total emissions of CO and organics in urban areas will increase from current levels of less than 1 per cent to 3 to 5 per cent over a ten year period.

REDUCTION OF AIRCRAFT ENGINE EMISSIONS

This section of the report comprises a description of the various available methods for reducing the quantities of pollutants that are emitted by aircraft engines. Whenever possible the effectiveness of each method is evaluated. For discussion purposes emission reduction methods can be categorized as follows:

1. Engine modifications
2. Aircraft modifications
3. Fuel modifications
4. Flight pattern modifications
5. Ground operations modifications

To be regarded as practical, an approach to reducing pollutant emission must be both effective and feasible. In other words, the approach must offer substantial reductions in pollutant emission without imposing unjustifiable costs on the operator of the source.

Modifications to Engines

It has been shown earlier that the nature and quantities of pollutants emitted from piston engines differs markedly from those from turbine engines. They will, therefore, be considered separately.

Piston Engines

The approach taken in this section involves a review of emission control measures in use in automobile engines, and, subsequently, a discussion of the practicability of applying similar measures to the control of exhaust emissions from aircraft piston engines. The subsection dealing with automobile emission control has been reproduced from Reference 73.

This material, in the opinion of the authors, represents a comprehensive review of the subject quite pertinent to control of emission from aircraft piston engines.

Exhaust Emission Reduction in Automobile Engines

Two major sources of air pollutants from the gasoline engine, the crankcase and the exhaust, are now subject to control.

Crankcase emission control systems have been required by law on all new cars sold in California starting with the 1963 model. However, control devices were installed voluntarily by automobile manufacturers starting with the 1961 models on almost all new vehicles produced for the California market, and subsequently for the entire country.

Commencing with the 1966 model year, most new cars sold in California were required to meet standards for content of pollutants emitted in the exhaust. These standards are being applied nationwide to all new automobiles beginning with 1968 models. The emission standards for motor vehicle contaminants are:

Hydrocarbons	--275 parts per million by volume as hexane. (0.165 mole per cent carbon atoms.)
Carbon Monoxide	--1.5 per cent by volume.

The California Motor Vehicle Control Board's compliance test procedure, commonly known as the "California Cycle" test, consists of a prescribed sequence of vehicle operating conditions on a chassis dynamometer using combined sampling of an exhaust gas through an analytical train.

This procedure is designed to simulate an average "trip" in a metropolitan area of twenty minutes from a cold start. The test consists of two parts: four 7-mode warm-up cycles and three 7-mode hot cycles (5th cycle not read). The average concentration of the warm-up cycles and the hot cycles are combined to yield the reported values. Exhaust gas concentrations are adjusted to a dry exhaust volume containing 15 per cent by volume of carbon dioxide plus carbon monoxide.

Hydrocarbons are defined as the organic constituents of vehicle exhaust as measured by a hexane-sensitive nondispersive infrared analyser or by an equivalent method.

The basis for the cycle was a field survey, made in Los Angeles a decade ago, to establish a typical driving pattern. The use of this cycle for system development and surveillance has been subject to criticism because it may not represent a realistic current vehicle use pattern, nor be applicable outside the urban Los Angeles area. Nevertheless, it is the only presently available universal testing procedure for determining and comparing the performance of exhaust emission control systems.

It is possible through control of certain design and operating variables to reduce the amounts of unburned hydrocarbons and carbon monoxide which are produced by an engine. The most important of these is carburetor mixture control. A survey run in California in 1956 showed average unburned hydrocarbon emissions were approximately 1400 ppm. The accuracy of this value may be open to question because of instrumentation problems associated with the survey. It is generally agreed, however, that the exhaust emission of current model automobiles not equipped with controls is approximately 900 ppm hydrocarbons. This suggests that evolutionary changes in engine design may be responsible for a substantial reduction in average exhaust emissions from vehicles not equipped with exhaust controls.

Other factors which can reduce emissions of hydrocarbons are: decrease in the relative amount of surface per unit volume of the combustion chamber; decrease in compression ratio; avoidance of dead space and pockets in the combustion chamber; optimization of ignition timing; the use of an automatic transmission; increasing average operating temperature; and freeing the combustion chamber from deposits.

Three means for reducing exhaust hydrocarbon and carbon monoxide are presently being utilized. The first is engine operation modification which incorporates leaner and more precisely controlled carburetor mixture ratios. This is accompanied by spark adjustment, particularly at low engine speed. The second development is the provision of air pumped into the exhaust manifold and directed into the exhaust gases immediately at the exhaust valves.

The last of the three approaches involves design and manufacturing considerations. Careful attention is paid to those factors which produce unburned hydrocarbons as a result of flame quenching or stagnant pockets and recesses in the combustion space outline. One example of a manufacturing improvement to reduce emissions is better matching between cylinder head and gasket.

Prior to the application of control devices, in-service vehicle exhaust gas hydrocarbon content was measured as 900 parts per million and carbon monoxide was about 3.5 per cent, using a cycle similar to the present California Cycle as the test procedure. In the average current production vehicle, these emissions have been reduced to approximately 275 parts per million of hydrocarbon and 1.5 per cent carbon monoxide as prescribed by the California standard. Controversy exists, however, with respect to how well the standards have actually been met, both in new cars as delivered and as tested after a few thousand miles of use.

Information on conformity of present systems to established standards, other than that from the manufacturers, comes from two sources, the State of California Motor Vehicle Pollution Control Board and the National Air Pollution Control Administration, U. S. Public Health Service. Reports from these two sources indicate that the present systems undergo progressive deterioration with time and operation. The systems start out well within control standards, but emissions are either equal to or exceed the limits after 10,000 miles of operation, which is approximately the average yearly mileage accumulation in California. Maintenance of carburetor and ignition adjustment are important factors. Obviously a system requirement which depends upon close maintenance will have more difficulty achieving long term conformity to a standard which is barely satisfied at the outset.

Because of variability in production, emissions from new cars will vary around an average value. Some of these may and do exceed stated standards, but certification is based on averages weighted on production volume. Obviously quality control is a factor which must be given close attention.

The data on which the performance of presently installed devices is based is relatively meager. The only specific data available at this time indicates that the hydrocarbon levels in a group of vehicles from the Los Angeles area have reached 282 parts per million after one year of operation. Various reasons for this exceeding of standards have been offered, including those of statistical reliability. These results are important, however, and if taken as received, they indicate that the average California vehicle meets the State standard for only a relatively short period of operation. There are insufficient data to indicate what might be the ultimate emission levels for those presently equipped vehicles.

Future Emission Control Methods

Considerable work is in progress in the automotive, petroleum, and other industrial laboratories, and in Federal installations, directed toward the development of future emission control systems for spark-ignition gasoline engines. Four approaches are being followed in this research: (1) modifications in the design or operating adjustments of engines to produce minimum emission levels in the exhaust gas leaving the engine cylinders; (2) post-cylinder exhaust treatment of reactive pollutant emissions prior to their exit from the tailpipe; (3) recycling of a portion of the exhaust gas to the engine intake to lower the temperature of engine combustion to reduce the production of nitrogen oxides; and (4) systems to prevent evaporation of gasoline from the carburetor and fuel tank.

Although it is generally agreed that hydrocarbon and carbon monoxide reductions are desirable, nitrogen oxide control is not required by Federal standards, nor is compliance with the California standard of 350 parts per million required until two or more control devices are tested and approved. However, control methods are being studied by industry and by government laboratories to meet California requirements in case a decision in favor of Federal nitrogen oxides control should be reached.

Engine Design

The engine modification (as opposed to air injection) systems for controlling hydrocarbon and carbon monoxide emissions, currently in production on some 1967 cars in California, rely predominantly on carburetion and spark-timing adjustments for their effectiveness. The use of these procedures requires either compromise with operational characteristics other than emissions or engineering improvements in the engine-carburetor system. Both carburetion and timing were originally optimized for other operational characteristics.

It has been found possible to improve carburetors and engine induction systems in general and to satisfactorily engineer spark-timing changes so that the necessary adjustments could be made. With engines having certain basic design characteristics, these adjustments are sufficient to attain the 1966 California or 1968 Federal emission standards.

Careful fuel control through advanced fuel injection systems as well as carburetors will permit optimization of air-fuel ratios for reduced carbon monoxide and hydrocarbon emissions. However, these systems increase cost and introduce design, manufacturing, and adjustment problems.

Other engine design factors which affect hydrocarbon and/or carbon monoxide emissions are:

displacement per cylinder
compression ratio
combustion chamber surface-to-volume ratio
parasitic volumes in the combustion chamber
combustion chamber surface temperature
valve timing

cylinder gas motion

Among the vehicle design factors affecting emission levels are:

weight and frontal area

power-to-weight ratio

rear axial ratio

transmission type

By careful optimization of all engine and vehicle design factors, along with suitable carburetion and spark-timing adjustments, it is likely that vehicles averaging 180 ppm hydrocarbon and 1 per cent carbon monoxide could be manufactured in the future. It is also likely that some vehicles could be manufactured at considerably lower levels, perhaps as low as 100 ppm hydrocarbons and 0.8 per cent carbon monoxide. However, if every vehicle were required to attain such levels by these means, severe limitations on the variety and versatility of vehicles marketed would be required, and many vehicle characteristics now taken for granted would be eliminated.

Many engine design and adjustment changes which effect reductions in hydrocarbon and carbon monoxide emissions unfortunately increase nitrogen oxide emissions. Almost any modification which increases engine thermal efficiency also increases nitrogen oxide emissions. The engine designer is thus faced with a dilemma if he seeks to simultaneously control all three emissions. At present it appears that the only solution to concurrent control of all emissions by engine design and adjustment factors alone would be operation with extremely lean combustion mixtures of greater than 18 to 1 air-fuel ratio. While such operation might be technically feasible, it is completely non-commercial at this time from the standpoint of a satisfactorily driveable vehicle.

Simple Air Injection

The exhaust port air injection control systems currently in production meet the 1966 California and 1968 Federal standards of 275 ppm hydrocarbons and 1.5 per cent CO, when weight-averaged according to sales volume. Although some minor improvements in these systems might result from further engineering development, e.g., optimized air flow, timed air injection, and more carburetor and spark-timing optimization, a major change in approach is required if further significant improvements in hydrocarbon and carbon monoxide reductions are to be made.

The simple air injection system has no appreciable effect on nitrogen oxide emissions.

Large Manifold Air Injection Reactors

Several laboratories have demonstrated exhaust emission control systems which deviate significantly in approach from the simple air injection systems now in production. These methods involve large exhaust manifolds (reactors) which give the exhaust gases additional residence time for reaction, and they employ insulation of some form for heat conservation. By thus providing increased time and temperature for reaction, they allow considerably better clean-up of hydrocarbons and carbon monoxide than do the simple air injection systems. Laboratory demonstrations on individual vehicles have attained emission levels of 27 ppm hydrocarbons and 0.8 per cent carbon monoxide. One such system currently undergoing life testing and still in operation had maintained hydrocarbons below 50 ppm and CO below 0.8 per cent for 50,000 miles.

While this demonstration of technical feasibility is certainly promising, it must be pointed out that there are serious obstacles remaining on the route to commercial feasibility with this system. Temperatures above 1000 deg F are required in the reactor to maintain effectiveness, but temperatures above 1700 deg F result in greatly decreased durability even if exotic and expensive construction materials are used. Severe damage from engine misfirings or backfires can occur. In addition, the space requirements under the hoods of cars, as they are designed today, are difficult to meet, and higher underhood temperatures from some configurations can be a problem. It is anticipated that with sufficient development time these problems, and others yet unknown, can be overcome without unreasonable costs.

The large manifold air injection reactors also have no direct effect on nitrogen oxide emissions. However, one combination of systems has been tried in which rich air-fuel mixtures are supplied to the engine, giving lowered nitrogen oxide emissions (approximately 500 ppm) but high hydrocarbon and carbon monoxide emissions. The hydrocarbon and carbon monoxide emissions are then subsequently reduced in the large manifold reactor. This arrangement puts a heavy heat load on the manifold reactor, and causes ~~some~~ loss in fuel economy, but it does present one means of making simultaneous attacks on all three emissions.

Direct-Flame Afterburner

The direct-flame afterburner is installed in the exhaust system and provides for flame oxidation of unburned fuel and carbon monoxide. As the term is commonly used, it does not include exhaust manifold air injection reactors. Afterburners must be provided with a supply of air to support combustion, and a spark plug and energy source to initiate burning.

These devices have a lean limit below which combustion cannot be maintained. For example, an afterburner will not ordinarily burn with the amount of chemical energy available in the exhaust with the usual cruising mixtures supplied to gasoline engines. Therefore, carburetor enrichment has commonly been used or additional fuel added in the afterburner, with attendant disadvantages and problems.

Catalytic Converters

During the years 1957-1964 considerable work was done in industry to develop catalytic converters for the reduction of hydrocarbon and carbon monoxide emissions. These converters operate quite effectively when new, but rapidly lose their effectiveness with increased miles of operation due to deposits from tetraethyl-lead fuel additives which coat the catalyst. After 12,000 miles of operation most catalytic converters fail to meet the California standards of 275 ppm hydrocarbons and 1.5 per cent carbon monoxide.

Work on catalytic converters was virtually stopped in 1964 when it became clear that the engine modification and air injection approaches were adequate for the 1966 standards. The limited life of the catalytic converters with leaded fuels was considered a serious disadvantage.

Today, when more stringent emission reduction requirements are a serious consideration, catalytic exhaust treatment is once more competing for attention since it has good potential for attaining very low hydrocarbon and carbon monoxide levels. Levels of 50 ppm hydrocarbons and 0.5 per cent carbon monoxide have been attained with the use of catalysts uncontaminanted by lead. To realize this control commercially, the lead contamination problem must be solved, and the most ready solution to this problem is the marketing of unleaded gasoline. This, in turn, represents an economic problem involving increased gasoline cost to the customer and higher capital investment for the oil industry. Lead "filters" or lead removal from exhaust by reaction ahead of the converter have also been proposed, but these have not proved successful as yet.

Even with unleaded gasoline, there is still some question about catalyst life. High temperatures for extended time periods tend to give "glazing" of the catalyst and reduce surface area. The effectiveness of the catalyst is thus reduced according to a time-temperature function, and some reports indicate lifetimes of less than 25,000 miles, even without lead. Other data suggests that catalysts may run as long as 50,000 miles with no deterioration under some conditions.

Since most catalytic converters require the addition of air to the exhaust for complete effectiveness, the possibility of combining them with current simple air injection systems is obvious. Assuming the lead problem is solved, this arrangement appears quite attractive, although numerous durability, packaging, and cost problems must still be overcome before commercial feasibility is proven.

Nitrogen oxide emissions may also be reduced by catalytic means, although no prototype system has yet been demonstrated on a car under a wide range of operating conditions. In general, the most feasible approach seems to be with rich air-fuel mixtures giving sufficient carbon monoxide to reduce the nitric oxide with a catalyst. The nitric oxide reduction catalyst is then followed by air introduction and a second catalyst bed to eliminate the remaining carbon monoxide and the hydrocarbons. The system appears complicated and costly, and its technical and economic feasibility has not been demonstrated.

Exhaust Recycling

The most effective system for reducing nitrogen oxide emissions appears to be exhaust gas recycling. In this system, 10 to 20 per cent of the exhaust gas is withdrawn from the exhaust manifold or exhaust pipe and with suitable flow controls is introduced in the intake manifold of the engine. This reduces peak cycle temperatures in the cylinder, and the burning rate is decreased, with significant reductions in nitrogen oxide emissions. Emissions levels below the California standard of 350 ppm have been attained by this procedure. However, problems still remain. The amount of recirculation is critical; too much increases the hydrocarbon and carbon monoxide and can cause losses in vehicle performance, power, economy, and driveability. Exhaust recirculation and lean mixture operation for hydrocarbon and carbon monoxide control appear to be entirely incompatible.

Nevertheless, a combination of exhaust recirculation with air injection permits simultaneous control of hydrocarbons, carbon monoxide, and nitrogen oxides within the current California standards with only driveability, and perhaps durability, as unsolved problems. These difficulties should be overcome with sufficient development time.

Estimated Attainments for Exhaust Control

In discussing probable attainments of future emission control systems, it is first necessary to define the present use of the term "feasibility." Two levels of feasibility are used in this discussion, as follows:

Demonstrated Technical Feasibility = Emission control at a given level has been achieved experimentally in the laboratory on at least one vehicle.

Commercial Feasibility = Emission control at a given level is attained on a vehicle which performs the required transportation function, is manufacturable, and is acceptable to the public in all respects, including economics, durability, performance, convenience, esthetics, psychology, etc.

From these definitions, it may be clear that it is a long and difficult obstacle course for any emission control system to travel from technical feasibility on one vehicle to commercial feasibility on approximately nine million vehicles per year. Nevertheless, the control systems used in California have surmounted these obstacles, and it is anticipated that in time some of the improved future systems described here will also reach production.

The table below indicates estimates of the levels of emissions and times of attainment for spark-ignition gasoline engines.

ESTIMATED CHARACTERISTICS OF FUTURE EMISSION CONTROL SYSTEMS[1,2]

DEMONSTRATED TECHNICAL FEASIBILITY

Year	1967	
Hydrocarbons ppm (as hexane).	50	275
Carbon Monoxide %	0.7	1.5
Nitrogen Oxides ppm	500	350

ULTIMATE FEASIBILITY

Hydrocarbons ppm (as hexane).	<25
Carbon Monoxide %	<0.25
Nitrogen Oxides ppm	<100

COMMERCIAL FEASIBILITY

Year	1967	1970		1975
Hydrocarbons ppm (as hexane)	275	180-200	275	50
Carbon Monoxide %	1.5	1.0-1.2	1.5	0.5
Nitrogen Oxides ppm	1500	600-800	350	250

(1) Spark-ignition gasoline engines tested according to California Standard Cycle Test Procedures for hydrocarbons and carbon monoxide (bag sample for nitrogen oxides) and weight-averaged according to vehicle sales volume.
(2) Table based on simultaneous attainment of the three (HC, CO, NOx) emission levels.

The demonstrated technical feasibility section of the table represents emission levels which have been attained in several laboratories. It may be noted, however, that difficulties exist in obtaining simultaneous low levels of hydrocarbon and carbon monoxide along with low levels of nitrogen oxides. Therefore, two possibilities are listed in the table depending on the particular combination of levels for the different emissions that are desired simultaneously. Although serious commercial problems still exist with both of the stated combinations, it is believed that these problems will be solved in a reasonable manner.

The expected ultimate control figures represent emission levels demonstrated for single pollutants in laboratory systems, but not levels which have been demonstrated simultaneously for all pollutants, even in laboratory systems. These emission levels may well be reached with sufficient development work some time after 1980.

The commercial feasibility figures for 1967 represent the emission control systems currently in production for new cars sold in California. These vehicles have no special control systems for nitrogen oxides. In 1970 it is believed that two possibilities exist. Either hydrocarbon and carbon monoxide levels can be reduced, and moderate reductions in nitrogen oxides can be obtained, or hydrocarbon and carbon monoxide can be left at their 1967 levels, and nitrogen oxide control to the 350 ppm level could be attained. In either case, problems with presently unknown solutions must be resolved in the intervening period.

Beyond 1970, it is anticipated that further commercial problems will be solved to the extent that the currently demonstrated technically feasible control systems can be put in production. In addition, some further improvements in carbon monoxide and nitrogen oxide control beyond the 1967 technical feasibility level are expected. If required, these levels could be attained with adequate notice to industry as early as 1975, but more optimized and less costly solutions will undoubtedly be available in later years.

Cost estimates for these future systems are more speculative. The 1967 systems add $25 to $50 to the vehicle sales price. It is estimated that, using the control system approaches described above, the emission levels in the table for commercial production in 1975-1980 might be attained at costs of $50 to $300 above that of the normal uncontrolled vehicle.

Application of Automobile Exhaust Emission Reduction Methods to Aircraft Piston Engines

In the preceding discussion, two "ultimate" approaches to reduction of most piston engine exhaust emissions have been identified:

1. Operation at very lean mixture ratios, or
2. Operation at very rich mixture ratios with auxiliary exhaust conversion devices.

The first approach is not presently feasible for the automobile and may never be feasible for aircraft piston engines because it involves a reduction in power to weight ratio. The other approach, however, would seem to be particularly appropriate to aircraft piston engines since, during the LTO-cycle, they operate at comparatively rich mixture ratios.

At the present time, methods for reducing exhaust emissions from automobiles can be regarded as interim methods. They satisfy current emission control requirements, but will not be adequate to meet future requirements. In the future, presently used emission reduction methods may be discarded in favor of improved methods.

Since aircraft piston engines represent a relatively small pollution source at the present time, it would be impractical for manufacturers of these engines to follow the same route to emission reduction as is being followed by automobile manufacturers. Rather than develop interim reduction methods, it would be more practical to work directly toward an "ultimate" approach offering emission levels which will meet future control requirements. Current emission loads could be tolerated during the period required for development of a practical emission reduction method.

The logical, long-term approach to control of emissions from aircraft piston engines is through exhaust gas conversion or afterburning. As mentioned previously, afterburning may occur naturally with aircraft engines due to the high temperature and fuel content of the exhaust gases. To the extent that natural afterburning is not sufficient to reduce emissions to an acceptable level, auxiliary devices can be employed. These include:

1. Exhaust port air injection
2. Large manifold air injection reactors
3. Direct-flame afterburners
4. Catalytic converters

At the present time, exhaust port air injection is the only feasible approach as the others have not been fully developed. Air injection could be adapted to new aircraft piston engines at approximately the same cost as with automobile engines, and similar emission reduction might be expected. As indicated in Table 38, concentrations of CO and organics in aircraft piston engine exhausts during idle and full power operation are in the following ranges: CO--6 to 12 per cent, and organics--7000 to 11,000 ppm. Reduction of these concentrations to levels currently attained in automobiles

(CO--1.5 per cent, organics--275 ppm) would constitute a reduction of CO emission of nearly 90 per cent and a greater reduction of organic emissions. The application of air injection reactors or direct-flame afterburners, which would require development effort, probably would result in even greater reductions in emissions.

Use of Alternate Engines

Another approach to reducing certain piston-engine emissions is the replacement of piston engines with turbine engines. Replacement is not feasible at present for light aircraft since turbine engines are not available in the low power ranges. Also, the costs of those which are available in the medium power range prohibit their use in most private aircraft applications.

On the other hand, replacement of piston-engine transport aircraft (class 5) by turbine-engine craft is occurring rapidly. These aircraft are being replaced by medium-range aircraft powered by turbofan engines (class 2). This substitution results in changes in emissions per aircraft approximately as follows: CO--96 per cent reduction, organics--95 per cent reduction, NO_x--200 per cent increase, particulates--110 per cent increase.

Turbine Engines

Considerable effort has been directed towards smoke abatement in aircraft turbine engines, as well as in gas turbines for other uses. Good descriptions of this work may be found in References 12, 13, 130, 131 and 132. Durrant (Ref 13) and Toone (Ref 130) describe the approaches taken at Rolls-Royce, Faitani (Ref 12) describes similar approaches at Pratt and Whitney Aircraft, and Fiorello (Ref 131) describes the U. S. Navy Smoke Abatement Program.

On the other hand, reduction of emission of other pollutants has not been studied extensively. As described earlier, emission levels of gaseous pollutants have been measured, but not correlated in a quantitative manner with engine design parameters. Durrant (Ref 13) does deal qualitatively with possible ways of controlling gaseous emissions.

For the purposes of this chapter, no distinction will be made between turboprop, turbofan, and turbojet engines. The emission of pollutants is dependent primarily upon combustion chamber design and operating conditions, and these do not vary substantially among different turbine engine types.

Smoke Reduction

It was explained earlier that carbon is formed by combustion of fuel-rich mixtures. In combustion chambers, smoke is produced from local pockets of fuel-rich mixture even though the mixture strength averaged over the combustion zone may be stoichiometric or fuel-lean. In a gas turbine combustor, the main source of carbon formation is in the primary combustion zone, and to reduce carbon formation, the fuel-air ratio in the primary zone should be kept to a minimum. This may be done in practice by increasing the air-flow into the primary zone, and by facilitating the mixing between the fuel and air. It is now possible by careful combustor design to greatly reduce smoke emissions without increasing the cost of the combustion chamber and without significant performance penalties (Ref 129). Durrant (Ref 13) states that the new large transport engines will have barely visible levels of smoke emission. Four major design approaches to smoke reduction which have been identified are discussed in the following paragraphs.

Reduce Primary Zone Fuel-Air Ratio

Durrant states that carbon formation in a Conway engine was reduced by a factor of 3 when the primary zone was operating at a stoichiometric fuel-air ratio. Faitani shows a reduction by a factor of 2 when the primary zone air-flow is increased from 15 per cent to 30 per cent. This method does involve certain penalties, however, including changes in combustion stability limits and ignition system requirements.

Increase Fuel-Air Mixing

Durrant also illustrates the benefits to be gained by increasing the penetration of the primary air jets. For a Tyne combustor, smoke reduction factors of 3 were obtained by increasing the pressure drop across the flame tube wall such that the total pressure loss in the chamber increased from 3.6 per cent to 4 per cent. This pressure loss represents an insignificant increase in specific fuel consumption. Faitani also found that improving primary zone mixing using directional tubes reduced smoke by a factor of 2. This reduction factor increases as the percentage of primary zone air increases.

Increase Fuel Spray-Cone Angle

Durrant indicates that increasing the spray-cone angle from a dual orifice injector from 95 degrees to 105 degrees reduces smoke by a factor of 2.

Changes in Fuel Droplet Size

Faitani found little change in smoke levels with varying droplet size, whereas Durrant reports an increase by a factor of 2 as the droplets increase from 50 to 100 microns. Fiorello (Ref 131) reports that decreasing droplet size increases smoke formation. These conflicts probably are due to the effects of differing atomizer and combustor geometries, and to interactions between droplet size and other combustor variables. In Reference 132, it is concluded that large drops may impinge on the walls forming carbon, whereas very fine droplets do not penetrate the primary zone, and thus cause local fuel-rich regions, leading to smoke. Therefore, to reduce smoke, small droplets must be accompanied by good mixing with the primary air.

Substantial reductions in smoke formation can be achieved if combustion chamber pressures are reduced. However, pressure reduction is not a practical solution to the problem. Not all of the potential reduction methods can be used simultaneously due to constraints associated with extinction and stability limits. However, improved combustor design appears to be the best approach to reducing smoke formation.

Smoke Reduction Attainable

Several methods of judging smoke density have been used for the evaluation of carbonaceous emissions in aircraft turbine exhausts (See Appendix 1). McDonald (Ref 133) discussed the problem of relating visibility in the plume to estimates of concentration of particulate matter using Mie-theory. More recently Faitani (Ref 12) has outlined the use of a modified "Von Brand Smoke Density" (VBSD) system for estimating exhaust opacity, and has suggested an opacity of 25 VBSD units (scale of 0-100) as "acceptable". This is reported by him to correspond to a concentration of particulate matter of less than 10 micrograms per liter of exhaust gas.

Rolls-Royce, Ltd. of England, using a "Photo Smoke Meter", has established a plume density of about 5 "Photo Smoke Units" (5 PSU), or a concentration of 5 micrograms of carbon per liter of exhaust gas as the density (or concentration) associated with the lower limit of visibility of smoke trails from aircraft turbine engines (Ref 13). This plume density is a highly desirable goal, and emission reductions to achieve it are possible.

Reduction of smoke emission to reduce exhaust plume visibility will also reduce the contribution by individual aircraft to community concentrations of particulate matter. At the present time, different engine models vary widely in their rates of particulate emission, and the degree of emission reduction required to render exhaust plumes invisible also varies. Certain engines will require a reduction in emission rate of the order of 80 per cent to reach the goal of 5 to 10 micrograms of carbon per liter of exhaust gas, while other engines meet this goal now. If all turbine engines were modified to meet this emission goal, it is estimated that the over-all reduction in particulate emission from aircraft engines would be approximately 50 per cent.

Reduction of CO and Organic Emissions

CO and organics can be considered together as they are produced in a similar manner and their emission rates can be reduced using similar approaches. As stated earlier, both of these emissions originate in the outer zone of the combustion chamber where the flame is chilled by the local injection of air needed to cool the liner walls. Emission rates decrease as throttle settings are increased such that, for most turbine engines, CO and organic emissions are negligible at top speed. The worst situation exists when the engines are idling. Under these conditions Durrant (Ref 13) reports that, for a Tyne engine, organic emissions can be reduced from 20 per cent to 1 per cent if the first cooling air strip is blanked off. However, this cooling is required to maintain the mechanical integrity of the walls.

Two practical approaches for reduction of these emissions do exist. They are:

1. The use of annular combustion chambers. For a given combustor requirement, the surface area of an annular chamber is less than for can or can-annular type combustors in current use, and, therefore, the cooling air requirements are less.
2. The use of fuel injectors that reduce the penetration of fuel towards the walls at the idle conditions.

Neither of the above approaches should add significantly to engine cost. However, there is insufficient data at this time to state confidently what emission reduction levels are practically attainable. Durrant states that the use of annular combustors can essentially eliminate organics and carbon monoxide at taxi conditions. However, the authors feel that a 50 per cent reduction in emissions is a more reasonable expectation. This estimate is based upon a comparison of emission data from one engine with an annular combustion chamber and emission data from other engines. (Engine T in Figure 15 has an annular chamber.)

Reduction of Oxides of Nitrogen

Oxides of nitrogen originate in the combustion chamber in regions of high temperature. NO_x emissions are expected to increase as engine pressure ratios and turbine inlet temperatures increase. To reduce NO_x emission, the maximum temperature in the combustor must be reduced. Durrant (Ref 13) suggests that this may be achieved by running with a richer primary zone, but this approach would increase smoke emission. The maximum temperature, and therefore NO_x emissions, can also be reduced by running the primary zone fuel-lean. This approach would make ignition problems more acute, and therefore, it is not possible at this time to predict whether the approach would be practical or economically feasible.

Modifications of Aircraft

In this section approaches to emission reduction through aircraft modifications are identified and evaluated. Modifications considered include changes in basic aircraft design and operational parameters such as wing loading and aircraft weight.

For all turbine-engine aircraft, the emission of carbon monoxide and organics during take-off, climb-out, approach, and landing, amount to 10 per cent or less of the total quantities emitted during an LTO-cycle (see Table 42). The other 90 per cent are emitted when the aircraft is on the ground and are not affected by aircraft design. Therefore, aircraft modifications would not be effective in reducing CO or organic emissions. On the other hand, between 60 and 70 per cent of the emission of CO and organics by piston engines occurs during the ground runs, approach and climb-out, and most of this occurs during climb-out. NO_x and particulate emission is of most concern from turbine-engine aircraft, and the greatest quantities of these materials are emitted during flight operations. Thus, reducing the duration of flight operations, and particularly the climb-out mode, would result in reductions in pollutant emission.

Aircraft characteristics which affect its rate of climb most strongly, assuming that engine thrust is not changed, are weight and wing-area. However, changes in these characteristics would result in less-than-proportionate changes in emissions. Consequently, the changes which would be necessary to substantially reduce emissions of pollutants would not be practical.

Other design variables which affect the durations of operational modes are thrust and braking power. Increases in thrust would, however, increase pollutant emission rates and offset any reduction in duration, unless accompanied by a reduction in engine specific fuel consumption. The braking power only affects the landing-run period which contributes, at the most, 12.5 per cent of the total NO_x load for turbine-engine aircraft (negligible for piston engines), and less than 5 per cent of the other pollutants.

From these observations, it is concluded that aircraft modifications do not offer practical approaches to reduction of pollutant emissions. Other approaches, such as engine modification, offer greater effectiveness and feasibility.

Fuel Modifications

If consideration of fuels for aircraft is limited to petroleum products (hydrocarbons), then little or no effects on the quantities of CO or organics emitted could be expected from fuel modifications. Changes in the character of organic emissions can be achieved, however, and the State of California currently employs fuel specifications to reduce the photochemical reactivity of organic emissions from automobiles.

Quantities of SO_2 emitted by aircraft could be reduced by lowering the sulfur content of aviation fuels. However, as stated earlier, the sulfur content of these fuels is very low at present and the costs of further reductions are not warranted.

Lead emission by aircraft piston engines could be reduced, as with automobiles, by reducing the lead content of gasoline. Low-lead or lead-free gasoline suitable for automobile engines can be used in most aircraft piston engines, but special fuels may have to be developed for high performance aircraft engines if lead is removed.

Particulate emission by aircraft turbine engines could be reduced by changes in fuel composition. Smoke formation is found to be less if certain fuel constituents are reduced to very low levels, or if lighter, highly-distilled fuels are used such as naphtha (Ref 131). These changes, however, are generally found to be very costly, and in some cases, result in an increased fire hazard. Since effective approaches to smoke reduction are available through engine modifications, fuel modifications are not considered practical at present.

Another approach to reducing smoke emission by turbine engines involves the use of additives. Experimental tests with different materials has revealed that certain metal compounds are effective in reducing smoke when added to the fuel in low concentrations (Refs 130 and 131). However, products of combustion of the additive materials are found to cause engine performance to deteriorate rapidly. Also, the effects of emissions of these additive materials in the community atmosphere are largely unknown. Because of these factors, smoke-reducing additives are not considered practical for general use in turbine engines.

If non-petroleum fuels, such as ammonia or hydrogen, are considered, emissions of CO, organics, and carbon can, in principle, be eliminated. However, conversion to such a fuel would present enormous problems associated with production, storage, and handling, as well as cost and safety. Thus, non-hydrocarbon fuels cannot be considered practical for emission reduction, at least in the near future.

Finally, we are not aware of fuel modifications which affect emission of nitrogen oxides. These pollutants are formed from the normal constituents of air at the high temperatures existing in engine combustion chambers.

Thus, there are a variety of approaches to emission reduction based upon modifications to fuels. But in nearly all cases, the effectiveness or feasibility of these approaches are less than those of alternative approaches.

Modifications to Flight Patterns

Most aspects of aircraft flight operations are determined by aircraft performance characteristics or safety considerations, and thus, are not subject to modification for purposes of emission reduction. Aspects which could, at least in principle, be modified include holding time, noise abatement procedures, and approach angle. The relationships between these factors and pollutant emission are discussed in this section.

Influence of Holding Time

All pollutant loads presented in this report are based upon operations below altitudes of 3000 ft. Any additional time spent in a holding pattern below 3000 feet will add to the pollutant load. However, the added CO and organic load due to holding is significant only for piston-engine aircraft, and the added load represents less than 4 per cent of the LTO-cycle CO and organic load per minute spent holding below 3000 ft. The equivalent added load for NO_x and particulates are higher for turbine engines, representing an additional 15 to 20 per cent load per minute of holding. Piston-engine aircraft contribute an additional 6 per cent load of NO_x and 2 per cent of particulates per minute of holding.

Effects of Noise Abatement Procedures

The added pollutant loads due to constraints imposed by noise abatement requirements are negligible. Although the aircraft spends more time climbing to 3000 ft, this increase in duration is offset, in the case of NO_x and particulates, by a reduction in emission rates. Carbon monoxide and hydrocarbon emissions are insignificant during this mode for turbine engines, and noise abatement requirements are not applicable to piston-engine aircraft. Therefore, noise abatement procedures do not significantly affect pollutant loading.

Changes in Approach Angle

The time spent on approach is inversely proportional to the approach angle. Therefore, if the approach angle is doubled, the approach time, and therefore, the emission load during approach is reduced by a factor of 2. In this case the following typical reductions can be expected in the total pollutant loading during an LTO-cycle:

	Piston Engine Aircraft (Per Cent)	Jet Engine Aircraft (Per Cent)
CO	8.0	< 1.0
Hydrocarbons	8.0	< 1.0
NO_x	12.5	12.5
Particulates	6.25	16.0

At this time, most aircraft descend at an approach angle of 3 degrees, and an increase to 6 degrees does not seem to be practicable. Also, the above data indicate that the pollution reductions resulting from a change in approach angle are small.

It is concluded from this discussion that, in general, reductions in emissions attainable through modifications in flight patterns are small. Also, changes in approach and climb-out operations are more likely to affect the safety of flight operations than other approaches to emission reduction. Consequently, modifications to flight patterns associated with landing and take-off operations are not regarded as practical. However, from the standpoint of reducing the impact of emissions from aircraft engines, unnecessary cruising flight at low altitudes over urban areas should be avoided.

Modification of Ground Operations

Substantial reductions in pollutant emission by aircraft at air terminals could be achieved by curtailing taxi operations. Auxiliary vehicles could be used to tow aircraft between the runway and the terminal, or to transport passengers to the aircraft at the runway. The latter system is in effect at the Dulles International Terminal serving Washington, D. C. Pollutant emission by the auxiliary vehicle must be considered as a counterbalancing factor. However, a number of low-emission engines are available for such special service vehicles.

Reductions in emissions also could be achieved by reducing the duration of operations with engines idling. Most idling time occurs in the waiting line at the take-off runway, and the duration of idling time increases rapidly with activity levels. Substantial reductions in emissions from idling could be achieved by having aircraft wait for take-off at the passenger loading area with engines off, thereby eliminating or reducing the waiting line at the runway.

The following table presents the relative contributions to total emissions from taxi and idle operations. These data are for a normal taxi time of 12 minutes (6 minutes for helicopters) and 1 minute idle.

Per Cent of Total LTO-Cycle Emissions Occurring During Taxi and Idle Modes

Aircraft Class	CO	Organics	NO_x	Particulates
1	98	79	14	12
2	88	83	19	9
3	95	97	39	20
4	89	72	45	30
5	22	17	55	25
6	39	41	50	25
7	84	85	14	28

It should also be noted the quantities of pollutants emitted during the taxi and idle modes vary linearly with times spent in those modes. It is observed from the table that most emissions of CO and organics by turbine-engine aircraft (classes 1, 2, 3, 4 and 7) occur during taxi and idle. The fractions of NO_x and particulates from these aircraft, and all emissions from piston-engine aircraft (classes 5 and 6), are less, but still substantial. These percentages represent the reductions in total emissions from aircraft which would be achieved if idle and taxi operations were eliminated. Nearly complete elimination of these operations could be achieved through the use of tow vehicles and modified ground operational procedures.

Emission Reduction Attainable

Certain of the approaches described above, if utilized, would be effective in reducing certain aircraft emissions from their present levels. Estimates of the potential reductions attainable at an individual air terminal and at all FAA-controlled terminals are shown in Table 63. It is clear from these estimates that CO and organic emissions at air terminals can be reduced substantially by using approaches which are currently feasible. Different approaches vary in their effectiveness among terminals because of differences in the types of aircraft activity. Similarly, a reduction in particulate emission would be expected, though the indicated reduction would be partially offset in the future by increases in aircraft activity. The net effect on particulates would be a reduction of visible smoke, but little change in total emission.

The major pollutants for which no effective reduction techniques exist are oxides of nitrogen. The combined effects of equipment changes, reduction of other pollutants, and increased aircraft activity will lead to a rise in NO_x emission. Similar trends exist in NO_x emission from other sources, including automobiles. However, no standards or other limitations on NO_x emission are in effect at the present time.

Reduction of Odors

The absence of information on odor precludes an evaluation of odor reduction methods. Nevertheless, certain basic considerations are discussed below, as an appraisal of the possible effects of control procedures on odors from aircraft engine emissions.

Greater Dispersal

The primary effect on odors that would be achieved by increased separation of airfields from densely populated communities, by activated carbon purification of intake air for passenger terminal buildings, and by similar procedures, is that of increased dilution between engine exhaust and people. The most recent and reliable series of reports on psychophysical scaling of odor intensity (Ref 134) indicate that the intensity is a power function of the odorant concentration; the exponents varying approximately in the range 0.5-0.7. Taking 0.6 as a typical exponent, we have

$$\text{Perceived psychological magnitude (odor intensity)} \sim \text{odorant conc.}^{0.6}$$

$$\text{or} \quad I \sim C^{0.6}$$

Example: An abatement procedure is 90 per cent efficient in reducing aircraft engine exhaust odorant concentration. What is its "psychological efficiency?"

$$\frac{I_1}{I_2} = \left(\frac{C_1}{C_2}\right)^{0.6}$$

If the odorant concentration is reduced by 90 per cent, then $(C_1 - C_2)/C_1 = 0.9$ and $C_1/C_2 = 10$ (where C_1 is the initial and C_2 the final value). Then $I_1/I_2 = 10^{0,6} = 4$, and the "psychological efficiency" $(I_1 - I_2)/I_1$, is only 75 per cent.

This material-to-psychological transformation itself may not be too serious. A problem that is more difficult, and to which there have been no significant approaches in the air pollution field, is the effect of frequency and duration of exposures to odor on the adverse reactions of people. Thus, a 90 per cent reduction in odorant concentration that might be accomplished by increased physical separation of people from aircraft engine emissions, resulting in a 75 per cent reduction in perceived odor intensity, represents an average value over a time span such as 1/2 hour or more. Under conditions of atmospheric turbulence, these average values may be exceeded by peaks whose odor impact we have no firm basis on which to evaluate.

More Complete Oxidation of Fuel

To the extent that fuel is oxidized to CO_2 and H_2O, its products are odorless. Intermediate oxidation products, however, may be more highly odorous than the fuel. Some examples are listed below.

Alkane hydrocarbons	Essentially odorless after only minimal dilution.
Alkene hydrocarbons	Typical so-called "gasoline" or "hydrocarbon" smell.

Alkylated aromatic hydrocarbons, especially n-alkyls.	"Oily hydrocarbon", or "fuel oil" odors.
-unsaturated acids and aldehydes from oxygenative cracking	Pungent, irritating odors
Aryl aldehydes from oxygenative cracking of substituted aromatics	Sweet, sometimes fruit odors.
Phenolics from oxygenative cracking of aromatics	Burnt odors

The above list is a very rough classification, but it does serve to alert the investigator to the fact that not all oxidations improve odor.

Masking and Counteraction Methods

It is possible to modify odor quality by adding more pleasant odors under conditions that do not involve any chemical changes. Such processes are called *counteraction* or *cancellation*, and *odor masking* or *reodorization*.

There has been some usage of masking agents for diesel exhaust, but no published scientific evaluation of the responses of people to the modified odor. If masking were to be applied as a control procedure for aircraft engine exhaust, the following considerations would be relevant.

Dispensing

The modifying agent must be dispensed into the exhaust stream at a point where the temperature is low enough so that the agent would not be destroyed. Appropriate equipment procedures would have to be developed.

Dilution

It would be necessary to ascertain that the modifying agent accompanied the exhaust stream with equivalent dilution to the points where odors were detected by people.

Evaluation

Measures of intensity and quality are inappropriate for evaluation of masking agents. Instead, a survey of acceptability by the affected populace would be necessary. Survey methods in the air pollution field, especially with regard to odor, are only poorly developed.

Reduction of Pollutant Impact

As an alternative to reducing emissions of pollutants by aircraft engines, methods of reducing the impact of these emissions offer, at least in principle, a means to the same end, i.e., elimination of the undesirable effects of air pollution. Methods of reducing impact, however, are far more limited than emission reduction methods. Nevertheless, certain approaches to impact reduction are worthy of consideration for local or temporary problems.

The abatement of the impact of aircraft engine emissions upon receptors within the terminal area, in the absence of effective emission control as discussed above, can be achieved by imposing barriers between planes and people in the form of air-conditioned structures with adequate treatment of intake air. The technology is well-established, and local control agencies could specify and enforce air quality standards for interior spaces, whether "workrooms" or places of public assembly.

Similar "barriers" could be provided for receptor populations, or potential populations, in the vicinity of existing or proposed airports, in the form of air-conditioned homes (Ref 135). The task would have greatly different scale and economic aspects, of course, and "retrofit" would be a different problem from new construction. This approach would not affect pollutant concentrations in the ambient air and thus would not reduce exposure of individuals while outdoors, but could substantially reduce the total exposure of a population.

Summary

In this section, methods of reducing quantities of pollutants emitted by aircraft engines have been identified and evaluated. Of the various approaches available, modifications of engines and aircraft ground operations offer the most practical methods of reducing emissions of primary concern--carbon monoxide, organics, and carbon. Pollutants associated with fuel additives or impurities--lead and sulfur--can only be reduced by modifications of fuels.

Engine modifications currently used and under development for automobile engines are equally applicable to aircraft piston engines. However, because of the low air-fuel ratios used in aircraft engines, their exhaust gases contain high concentrations of organics. Consequently, emission reduction methods based upon exhaust gas conversion through combustion with added air appear to be most practical.

Modifications to aircraft turbine engines which would be effective in reducing emissions are certain changes in combustor design. Specific changes known to be effective are (1) reduction of primary zone fuel-air ratio, (2) improved mixing of fuel and air in the primary zone, (3) improved fuel injection at low power conditions, and (4) reduction of combustor surface area. The first two changes are effective in reducing carbon emission, and the latter two changes are effective in reducing CO and organic emissions at low power (idle) conditions.

Since substantial fractions of aircraft engine emissions are produced during the taxi and idle operating modes, reductions in the durations of these modes (or reductions in requirements for engine operation) will be effective in reducing quantities of pollutants emitted. Approaches to reducing the durations of these modes which are considered practical are (1) the use of auxiliary tow vehicles for aircraft, and (2) modifications of operational procedures which would reduce the time spent by aircraft with engines idling.

The reductions in emissions attainable by these methods vary at different terminals because of differences in activity levels among the various types of aircraft. At major air carrier terminals where most activity consists of turbine-engine transport aircraft, the most effective emission reduction methods would be modifications of ground operations and turbine-engine combustors. At general aviation terminals where most activity consists of piston-engine aircraft, modification or replacement of piston engines would be the most effective approach.

It is concluded that practical approaches are available for reducing emissions of CO, organics, and particulates from aircraft operations at air terminals by factors of 60 to over 90 per cent. On the other hand, no practical methods for reducing NO_x emission are presently available.

CONTROL OF AIRCRAFT ENGINE EXHAUST EMISSIONS

The two basic aspects of emission control--control requirements and control methods--are discussed in this section as they pertain to aircraft engine exhaust emissions. In dealing with the matter of control, we are confronted with the interesting question of how to classify aircraft as an emission source. Air pollution control agencies generally recognize two basic source categories--stationary sources and motor vehicles--and aircraft, at the present time, are included in the latter. However, an alternate approach, that of dealing with an air terminal as a stationary source, offers certain advantages. Both approaches will be discussed in this section.

Control Requirements

In determining the degree of emission control required of a particular source of pollutants, such as aircraft engines, various criteria can be utilized, depending upon the objective of the control measures. For discussion purposes, control objectives and associated criteria can be classified as follows:

Condition	Control Objective	Control Criterion
1. Local hazard	Eliminate local hazard from specific source.	Reduce source strength sufficiently to eliminate hazardous conditions.
2. Community hazard	Reduce contribution to community pollution during danger periods.	Eliminate unnecessary operations.
3. Local area pollution	Reduce contribution to local area pollution.	Reduce emission levels by all "effective and feasible" means.

Condition	Control Objective	Control Criterion
4. General community pollution	Reduce contribution to general community pollution.	Reduce emission levels by all "effective and feasible" means.
5. Sensory effects	Eliminate sensory or esthetic impact.	Eliminate through normal procedures, as practicable.

The first two categories include severe conditions of a temporary or highly localized nature, and their control requires prompt action which also may be temporary or localized. Categories 3 and 4 pertain to long-term, average pollutant levels, either in a local area, such as an air terminal, or over the entire community. Control of these conditions requires permanent, widespread emission reduction measures. The last category includes special conditions of an esthetic nature for which special action is required. This classification is general and, as such, is applicable to any type of pollutant source. A set of criteria such as this is necessary in dealing with a unique source such as aircraft, for which existing control criteria are not applicable.

Local Hazards

The local hazard condition is defined as including localized situations of an urgent or emergency nature requiring immediate control measures. Local hazards arising from aircraft operations have not been identified, but investigations of potentially hazardous conditions have not been exhaustive. As mentioned previously, it is conceivable that hazardous pollutant levels could arise as a result of various aircraft ground operational procedures.

It is concluded that controls on aircraft emissions are not warranted at present for the purpose of eliminating localized hazards at air terminals. However, monitoring of pollutant levels at certain locations within terminal areas is advisable. Locations where the potential hazards are greatest are take-off runways and passenger loading areas. If hazardous pollutant concentrations are encountered, they should be eliminated by appropriate modifications in aircraft ground operations.

Community Hazards

The community hazard condition is a community-wide pollutant condition requiring immediate, but temporary, control action. Such a condition is referred to as an air pollution episode and results from peculiar meteorological conditions wherein community atmospheric ventilation is reduced. When such conditions exist, aircraft operators should be expected to eliminate unnecessary flights involving aircraft with a high pollutant emission potential. Additionally, ground operational procedures at air terminals should be modified to reduce the duration of operations involving engine idling. Specific measures should include:

1. Curtail unnecessary flights by general aviation aircraft, or, alternatively, flights by piston-engine aircraft without emission controls.
2. Reduce aircraft holding time prior to take-off. Have aircraft hold at passenger loading area, with engines shut down, until clearance is given to proceed to runway for take-off.
3. Eliminate use of main engines for supplying auxiliary power during passenger loading.

These measures would require little advanced preparation and should be put into effect whenever necessary.

Local Area Pollution

Local area pollution is defined here as a long-term pollutant condition existing over a limited area. Such a condition has local impact as discussed in the previous section. With regard to aircraft, the impact of exhaust emissions in the vicinity of major air terminals is found to be comparable to the impact in urban areas of pollutants from other sources. Other sources of pollutants are presently being subjected to emission controls which will become increasingly stringent with time. As a result, the impact of emissions from these sources is expected to decrease. The impact of aircraft emissions, however, is expected to increase unless control measures are adopted, and this impact may become serious in the future.

It is clear that controls will be required to reduce aircraft emissions at major air terminals. Action must be taken by the aviation industry to reduce emissions by all measures which are effective and feasible, and such measures should be taken as soon as possible. Specific measures which would be appropriate under this criterion are:

1. Incorporation of emission reduction features in all new aircraft piston engines, including replacement engines.
2. Modification of current and new models of aircraft turbine engines to reduce CO, organic, and particulate emission.
3. Introduction of tow-vehicles for ground movement of transport aircraft with uncontrolled engines.

These measures will require equipment development effort, but no advances in technology. It is estimated that they could be in effect within two to three years from initiation of development. These measures are considered to be feasible and practical, and, as indicated previously, will be effective in substantially reducing emissions of CO and organics.

General Community Pollution

General community pollution is the result of the mixing of pollutants from all sources and it is manifested as a background pollutant level existing throughout the community. To reduce general community pollution, operators of all sources of air pollutants must reduce these emissions by every measure which is feasible and effective. The relative contribution of a particular source to community air pollution is not a factor in deciding whether emission reduction should be undertaken. The magnitude of a source can only affect an appraisal of the urgency of the emission reduction requirement.

In the case of aircraft, the measures necessary to reduce local area pollution also will be effective in reducing community pollution. Thus, the community-wide problem presents additional justification for control of aircraft emissions.

Sensory Effects

Pollution problems causing sensory effects, but not hazards, should be dealt with on a practical basis which will assure their eventual elimination, but not at undue cost to the operator of the source. Smoke trails and odor from jet aircraft are deemed to fall in this category.

Engine manufacturers have developed the capability of producing engines whose exhaust trails are marginally visible. This capability is expected to improve with time until engines are produced with near-zero particulate emission rates. Exhaust trails from these engines will be well below the visibility threshold. Thus, we can expect that future production of current engine models and newly developed engines will be smoke-free, or nearly so.

Engine manufacturers have the capability to "retrofit" existing engines with low-smoke burners, and this substitution is expected to take place gradually as burners are replaced during normal maintenance procedures. Since the smoke problem cannot be regarded as more than an annoyance, additional expenditures by aircraft operators to hasten the installation of low-smoke burners would not be justified. However, a more compelling reason for leaving the smoke problem to normal maintenance is the desirability of directing the resources of engine manufacturers and aircraft operators toward reduction of emissions which constitute more significant problems; notably, CO, organics, and--in the long run--nitrogen oxides.

Similarly, the elimination of odors from turbine engines is desirable, but, in this case, odor-reduction methods have not as yet been developed. Whenever practical techniques for odor-reduction are available, they should be adopted by operators of turbine-engine aircraft.

Approaches to Emission Control

Two basic approaches to the control of aircraft emissions are worthy of consideration. In the first, aircraft would be treated as motor vehicles and subjected individually to emission controls. In the second approach, an air terminal would be treated as a stationary source and controls would be applied to total emissions from aircraft within the terminal area. These approaches are not mutually exclusive. They could, indeed, be employed jointly to achieve substantial reductions in aircraft emissions.

The approaches differ, however, in their suitability for use by different government agencies. The first approach, that of treating an aircraft as a motor vehicle, is best applied by the Federal government. The aviation industry, even more than the automobile industry, is interstate in character and a uniform national control system would be desirable. Also, Federal registration, certification, and inspection procedures, already in effect, could be utilized to support an emission control program directed at individual aircraft.

The second approach, that of treating air terminals as stationary sources, is more amenable to use by state, regional, or local governmental agencies. Control criteria might be established by the Federal government (NAPCA). However, imposition of controls would be best accomplished by local authorities in accordance with local abatement requirements.

Aircraft as Motor Vehicles

Approaches to Emission Control

Approaches which can be taken by the Federal Government to reduce the emission on the impact of pollutants from aircraft engines fall into six categories. These are listed below with the most direct approaches listed first.

(a) Specification of exhaust emission standards
(b) Regulation of aircraft applications
(c) Regulation of aircraft operations
(d) Taxation
(e) Government procurement
(f) Research and development funding

Each of these categories is discussed in the following paragraphs.

Specification of standards is the most direct approach to exhaust emission reduction. It is being used by the Federal government for the control of emissions from many types of pollutant sources, including automobiles. In principal, an emission standard can be very effective in that it simply prohibits the sale or operation of sources which do not conform to the standard. In actual practice, however, the circumstances under which standards can be effective are limited. Limitations stem from the ability of operators of pollutant sources to conform to the standards, and the ability of government agencies to enforce the standards.

In the case of aircraft emissions, various pollutant types could be controlled by the application of standards to either engines or fuels. Standards on emission of CO, organics, and particulates could be imposed on new aircraft engines, provided that engine manufacturers were given sufficient lead time to incorporate the necessary modifications in engines currently in production. There is, however, no basis at present for setting a standard on emission of oxides of nitrogen from aircraft engines.

If engine emission standards are established, they would logically be based upon total emissions during a landing-take-off cycle. This approach would be consistent with the current controls on automobile emissions which are based upon a standard operational cycle. Also, it would be more practical to impose standards on emissions by engines rather than aircraft since the numbers of engine manufacturers and engine models in production are far fewer than the corresponding numbers of aircraft manufacturers and models.

Standards could be imposed on aircraft fuels to control emission of SO_2 and lead. Because of the basic similarity of aviation and automobile gasolines, they are amenable to similar standards. If standards are established on the lead or sulfur content of gasoline, the standards should apply to both automobile and aircraft fuels. Aircraft turbine fuels do not contain lead, and their sulfur content is limited to relatively low values to prevent corrosion of engine elements. The costs associated with further reductions of sulfur content could not be justified.

Regulation of aircraft applications is an approach available to the Federal government through its aircraft certification and registration procedures. Conceivably, aircraft which are strong sources of air pollutants could be denied certification for types of service involving high rates of activity in metropolitan areas. At first glance, this approach is appealing in that it appears to be selective toward aircraft making the greatest contribution to urban pollution. There are very few aircraft types, however, that do not regularly or occasionally operate from urban air terminals. Consequently, the effect of this approach would be the same as that resulting from the establishment of emission standards applicable to all aircraft. Aircraft certification and registration procedures will be most useful in the enforcement of emission standards or in providing a basis for pollution emission taxation. These procedures offer no unique advantages as primary control measures.

Regulation of aircraft operations is an approach which could be used, at least in principle, to reduce emissions at FAA-controlled air terminals. The FAA establishes operational procedures during the approach and climb phases of an aircraft LTO-cycle. To the extent that these procedures can be varied without compromising factors such as safety and noise abatement, they might be manipulated to reduce the aircraft emission load.

However, emission reductions attainable by this approach are small, and it does not appear that the Federal government can deny an aircraft access to a terminal on the basis of its emission chracteristics. Therefore, operational regulation does not offer the Federal government a means to effective pollutant control. On the other hand, control of ground operations could be an effective approach by local government agencies.

Taxation as a means of air pollution control can be effective in circumstances where an aircraft operator has a choice between options which result in different pollutant contributions. Such options might include equipment types, fuel types, or air terminals. In any of these categories, taxation could be used to encourage the operator to choose the alternative involving the lower pollutant load potential. Taxation offers the additional advantage of providing revenue useful for the support of pollutant control programs.

Taxes on equipment could be imposed as sales taxes or as use taxes in the form of increased registration fees and could be based upon pollutant emission rate. Taxes on fuels would logically be imposed as sales taxes and would be based upon lead or sulfur content. Taxes on air terminal usage could take the form of increased landing fees also based upon pollutant emission. However, since the assessment of such fees is performed by the air terminal operator, this approach could not be adopted readily by the Federal government.

Thus, it appears that taxation might be utilized to induce the same reductions in emissions which might otherwise be achieved by the establishment of emission or fuel standards. There are two considerations dictating against taxation, however. The first and foremost is that taxation does not assure emission reduction unless tax rates are prohibitively high. In this case, the effect would be the same as creating standards and imposing penalties for noncompliance. The second consideration is that taxation has not been used to date in the United States as an air pollution control method and it seems inappropriate to establish a precedent for taxation by applying it to a minor source of pollutants such as aircraft.

Government procurement has been used by the Federal government as a means for inducing automobile manufacturers to incorporate certain safety features in automobiles. By specifying such features on cars purchased by the government, the manufacturers have been forced, as a practical matter, to incorporate the same features in their entire production. A comparable situation exists in the aircraft industry to a limited extent. The Federal government is a major purchaser of aircraft turbine engines. By specifying emission standards for government purchased engines, the emission loads from military aircraft could be reduced, and the technology would exist for reducing emissions from civilian versions of the same engines. A precedent for this approach is being established by the U. S. Navy in proposing standards on smoke emission from its engines. The Federal government does not purchase significant numbers of aircraft piston engines, and thus, cannot exercise the same leverage in bringing about a reduction in piston-engine emissions. However, the Federal government is a substantial consumer of aircraft fuels, and by this approach could reduce emissions which are associated with fuel composition.

Research and development funding will be necessary to provide the techniques for reducing pollutant emission rates below levels currently attainable. R and D will be required on piston-engine emissions, turbine-engine emissions, and fuel modifications. The Federal government should participate in the funding of such activity.

Air Terminals as Stationary Sources

Classification of an air terminal as a stationary source of air pollutants provides a basis for control of aircraft emissions by local authorities. Control measures would consist of restrictions on aircraft operations, or engine operating time. Criteria for such control measures should be established by the NAPCA and based upon differences in engine pollutant emission as determined by standardized measurement techniques. A distinct advantage of this approach is that the degree of control can be varied with time and with terminal location in response to local air quality conditions.

Implementation of the control of emissions at air terminals requires that emission standards be defined. A logical basis for such a standard would be an average emission density over the terminal area. That is, the rate of emission of pollutants per square mile of land area would be limited. The limit on emission density might be set to be consistent with limits imposed on other urban areas, or might be selected on some other basis.

Steps which can be taken by the air terminal operator to comply with emission limits have been described earlier. These include:

1. Curtailment of all activities by aircraft with high emission rates. The basis for such curtailment might be emission per passenger rather than simply emission per aircraft.
2. Reduction of engine operating time during aircraft ground movements. Reduction could be accomplished by changes in

operating procedures, or by provision of auxiliary tow vehicles.

3. Reduction of emission from other sources associated with aircraft operations including auxiliary power sources, and deicing and maintenance procedures.

Minimization of pollutant emission has not been a factor in the establishment of air terminal operational procedures. Thus, it is expected that considerable reduction of emissions can be accomplished through revisions of operations without seriously affecting passenger and cargo transportation.

RESEARCH NEEDS

During the course of this study, a number of subject areas have been identified wherein further research is required to reduce uncertainties in the assessment of pollutant emissions by aircraft and their impact. Research also is required to evaluate approaches to the reduction of pollutant emission by aircraft. These research needs have, in many cases, been identified in the text of this report. This section contains a summary of these needs which is suggested as a basis for planning of future research on aircraft emissions and their control.

Aircraft Emissions and Emission Reduction

Piston Engine Emissions

1. The nature and extent of piston engine emissions should be determined as affected by engine size, type, and operating condition. Of particular interest are differences in the character of aircraft emissions from those of automobile emissions.
2. The degree of afterburning occurring naturally with piston engine emissions should be determined as it is affected by engine type, size, and operating condition, and by aircraft configuration and operating mode.
3. The effectiveness of emission control methods as applied to aircraft piston engines should be determined. Particular emphasis should be placed on exhaust gas conversion techniques.

Turbine Engine Emissions

1. Further study of turbine engine emissions is necessary to reduce uncertainties in rates of emission, particularly during taxi and idle modes. The nature of organic and particulate emissions from turbine engines also warrants further study.
2. Mechanisms of formation of nitrogen oxides in turbine engine combustors should be studied. The results of such studies should lead to methods of correlating NO_x emission with engine design and operating variables, and to methods of reducing NO_x emission.
3. Research on turbine engine combustor design should be continued to determine effective approaches to emission reduction. Particular emphasis should be placed upon low power operation for application to current problems. However, ultimate solutions to long-term problems also should be studied.
4. A study of sampling and analysis techniques is required for characterizing organic emissions from aircraft turbine engines. The objective of this study should be to develop techniques applicable to exhaust gases containing organic compounds of high molecular weight and low volatility.
5. Studies of ground operations at air carrier terminals are warranted to determine modifications in ground operational procedures which would be effective in reducing emissions.

Other Sources

1. Studies of other sources of air pollutants associated with aircraft operations are necessary to determine total pollutant

emissions at air terminals. Sources of concern not included in this study are auxiliary power units, service vehicles, fuel transfer and storage facilities, and aircraft servicing operations such as painting, cleaning, and deicing.

Impact of Aircraft Emissions

1. The initial mixing process by which the high temperature, high velocity exhaust stream is reduced to ambient atmospheric conditions should receive special study. This "transition zone" mixing will generally be determined by the exhaust velocity and temperature, exhaust nozzle design, engine grouping, aircraft configuration, aircraft velocity, and meteorological conditions. When the mechanics of this transition zone mixing can be described, it will be possible to model subsequent dispersion of the exhaust products. Analytical studies of initial mixing and subsequent transport of exhaust products is recommended for three cases:
    a. Fumigation of terminal building and neighboring work areas by aircraft near passenger loading areas.
    b. Contamination of intake air for crew and passenger cabins in aircraft waiting for take-off.
    c. Repeated exposure of land areas immediately adjacent to runways at major air terminals.
2. Field measurements should be made of pollutant concentrations at ground level within and around major air terminals. Such data are required to verify and improve models of pollutant

dispersion from individual aircraft and from air terminal operations involving many aircraft.

3. Studies of measurable effects of aircraft emissions on persons and property should be conducted.

Related Areas

Effort should be continued on studies of pollutant emission problems which are not unique to aircraft engines. Such problems include:

1. Emission and effects of lead compounds
2. Emission of odors
3. Complaint behavior of persons exposed to air pollutants

The need for study of these problems has arisen as a result of pollutant emission from automotive vehicles as well as aircraft. Solutions to these problems, when they are developed, will be applicable to both types of sources.

REFERENCES

1. George, R. E., and Burlin, R. M., Air Pollution from Commercial Jet Aircraft in Los Angeles County, Air Pollution Control District, County of Los Angeles, April, 1960.

2. Report of the Program Study Group on Aircraft Exhaust, Aviation Fuel Lubricant, and Equipment Research Committee of the Coordinating Research Council, Inc., August, 1960, Revised: December, 1960.

3. Lemke, E. E., et. al., Air Pollution from Aircraft in Los Angeles County, Air Pollution Control District, County of Los Angeles, December, 1965.

4. Dommasch, D. O., Sherby, S. S., Connolly, T. F., Airplane Aerodynamics, Pitmans, New York, 1957.

5. Perkins, C. D. and Hage, R. E., Airplane Performance Stability and Control, J. Wiley & Sons, Inc., 1965, p. 197.

6. Jane's All the World's Aircraft, 1967-1968, McGraw-Hill Book Company, New York, 1967, (also previous editions).

7. Private Communication - Boeing Aircraft Company, June, 1968.

8. McKinley, J. L. and Bent, R. D., Powerplants for Aerospace Vehicles, Third Edition, McGraw-Hill Book Company, New York, 1965.

9. Borden, N. E., Jr., Jet-Engine Fundamentals, Hayden Book Company, Inc. New York, 1967.

10. Owner's Manual, Model 172 and Skylark, Cessna Aircraft Company, Wichita, Kansas, 1968.

11. Two Ten Centurion, Cessna Aircraft Company, Wichita, Kansas, 1968.

12. Faitani, J. J., Smoke Reduction in Jet Engines Through Burner Design (SAE Paper No. 680348), Society of Automotive Engineers, New York.

13. Durrant, T., The Control of Atmospheric Pollution from Gas Turbine Engines (SAE Paper No. 680347), Society of Automotive Engineers, New York.

14. FAA Statistical Handbook of Aviation, Federal Aviation Administration, 1967 Edition, November, 1967, (also previous editions).

15. Federal Aviation Administration, Aeronautical Center, direct communication, June, 1968.

16. Aviation Forecasts, Fiscal Years, 1968-1979, Federal Aviation Administration, January, 1968.

17. Aerospace Facts and Figures, 1968, Aerospace Industries Association of America, Inc., Aero Publishers, Inc., Fallbrook, California, 1968

18. Brooks, Peter W., The World's Airliners, Putnam, London.

19. Aviation Week & Space Technology, Forecasts and Inventory Issue, March 18, 1968.

20. Census of U. S. Civil Aircraft as of December 31, 1965, Federal Aviation Administration, April, 1967.

21. 1968 Air Transport Facts and Figures, Air Transport Association of America.

22. Scheduled Air Taxi Operators as of October, 1967, Federal Aviation Administration.

23. Office of the Assistant Secretary of Defense, Installations and Logistics, direct communication, June 27, 1968.

24. Esso Air World, Supplement, May-June 1968, "Turbine-Engined Fleets of the World's Airlines, 1968".

25. Flight International, November 23, 1967.

26. "PT6 - Powered Aircraft Operators of the World", United Aircraft of Canada Limited, September, 1968.

27. Bureau of the Census, "Current Industrial Reports, Series M37G".

28. Rolls-Royce Limited, Aero Engine Division, direct communication, September 2, 1968.

29. FAA Air Traffic Activity, Calendar Year 1967, Federal Aviation Administration, February, 1968.

30. Military Air Traffic Activity Report, Calendar Year 1967, Federal Aviation Administration, July, 1968, (also previous editions).

31. Scheduled Air Carrier Flight Activity in the United States, May 1967, Federal Aviation Administration, November, 1967.

32. Airport Activity Statistics of Certificated Route Air Carriers 12 Months Ended December 31, 1967, Civil Aeronautics Board and Federal Aviation Administration, September, 1968.

33. Rogers, W. A., An Index of U. S. Naval Aircraft, Air-Launched Guided Missiles and Their Powerplants, Engine Program Information Center, Naval Air Systems Command, Washington, D. C., December, 1967.

34. Terminal Area Air Traffic Relationships, Fiscal Year 1965, Federal Aviation Administration.

35. Official Airline Guide, Quick Reference North American Edition, Reuben H. Donnelley Corporation, Oak Brook, Illinois, May 1, 1968.

36. Official Airline Guide, Quick Reference International Edition, Reuben H. Donnelley Corporation, Oak Brook, Illinois, May, 1968.

37. Sanders, W. N. and Maynard, J. B., Determination of the Detailed Hydrocarbon Composition and Potential Atmospheric Reactivity of Full-Range Motor Gasolines (Paper No. 68-8), Air Pollution Control Association Meeting, St. Paul, Minnesota, June 23-27, 1968.

38. Oil Statistics, Supply and Disposal, Organization for Economic Cooperation and Development, Paris, 1968.

39. International Petroleum Encyclopedia, Petroleum Publishing Company, Tulsa, Oklahoma, 1968.

40. Dukek, W. G., Esso Air World, vol. 17, no. 5, April, 1965.

41. "Tentative Specifications for Aviation Gasoline", ASTM Standards (D 910-65T), Part 17, October, 1965.

42. A Review of Aviation Fuel Controversy by the Air Safety Group, 11 South Square, Gray's Inn, London WC1, England.

43. Blade, O. C., Aviation Fuel 1963, U. S. Department of the Interior, Bureau of Mines, Petroleum Research Center, Bartlesville, Oklahoma, 1964.

44. Horstman, H. W. and Jackson, J. L., Combustion Characteristics of Special Hydrocarbon Jet Fuels (ASD TDR-62-682), Wright Patterson Air Force Base, Ohio, 1962.

45. Brockman, W. E. and Duvall, D. S., Physical and Chemical Properties of JP-4 Jet Fuel for 1966 (AD 660957), University of Dayton Research Institute.

46. Shayeson, M. W., Reduction of Jet Engine Exhaust Smoke with Fuel Additives (SAE Paper No. 670855), Society of Automotive Engineers, New York.

47. "Luminometer Numbers of Aviation Turbine Fuels", ASTM Standards (D1740-60T), Part 17, January, 1966.

48. Jenkins, G. I. and Walsh, R. P., Quick Measurement of Jet Fuel Properties, Hydrocarbon Processing, vol. 47, no. 5, May, 1968.

49. "Tentative Specifications for Aviation Turbine Fuels", ATSM Standards (D 1655-65T), Part 17, October, 1965.

50. Strauss, K. M., Fuels for the Supersonic Transport (SAE Paper No. 650-297), Society of Automotive Engineers, New York.

51. Lewis, A., "Fuels for Supersonic Aircraft", Science Journal, September, 1967.

52. Opdyke, G., Initial Experience with Emulsified Fuels at Avco Lycoming (SAE Paper No. 670366), Society of Automotive Engineers, New York.

53. Churchill, A. V., Hager, J. A. and Zengel, A. E., Fuels for Advanced Air-Breathing Weapon Systems (SAE Paper No. 650804), Society of Automotive Engineers, New York.

54. Petroleum Facts and Figures, 1967 Edition by American Petroleum Inst.

55. Pratt & Whitney Aircraft Division, United Aircraft Corporation, direct communication, June 18, 1968.

56. Aero Engine Division, Rolls-Royce Limited, direct communication, September 9, 1968.

57. Stern, A. C. (ed.), Air Pollution, vols. 1 & 2, Academic Press, New York, New York, 1968.

58. Magill, P. L., Holden, F. R. and Ackley, C., Air Pollution Handbook, McGraw-Hill Book Co., Inc., New York, New York, 1956.

59. Threshold Limit Values for 1967, American Conference of Governmental Industrial Hygienists, 1967.

60. Leighton, T. A., Photochemistry of Air Pollution, Academic Press, New York, New York, 1961.

61. State of California, Department of Public Health, Clean Air Quart. 9, 1, 1965.

62. Department of Health, Education and Welfare, Public Health Service, "National Air Sampling Networks and Contributing State and Local Networks, 1964-1965", Cincinatti, Ohio, 1966, p. 125.

63. Appleman, H., "A Note on the Effect of Aircraft Exhaust on Airport Visibility", Am. Meteorol. Soc. Bull. 37, #1, 19, 1956.

64. Clodman, J. "Visibility Deterioration Associated with Operations of Jet Aircraft", Bull. Am. Meteorol. Soc. 37, #7, 1956.

65. Ingram, W. T. and McCabe, L. C., "Air Pollution Effects on Airport Visibility", Ind. Wastes 3, 105, 1958.

66. McDonald, J. E., "Visibility Reduction due to Jet-Exhaust Carbon Particles", J. Appl. Meteorol. 1, 391, 1962.

67. Sawyer, R. F. and Starkman, E. S., Gas Turbine Exhaust Emissions, (SAE Paper No. 680462), Society of Automotive Engineers, Inc., May, 1968.

68. Direct Communication, Pratt & Whitney Aircraft Division, United Aircraft Corporation, July 22, 1968.

69. Rose, Jr., A. H., "Automotive Exhaust Emissions", Air Pollution, A. C. Stern, Editor, First Edition, Academic Press, New York, Chapter 20, vol. II, 1962.

70. Huls, T. A., Myers, P. S. and Uyehara, O. A., "Spark Ignition Engine Operation and Design for Minimum Exhaust Emission", SAE Progress in Technology, vol. 12, "Vehicle Emission, Part II", p. 71.

71. Brownson, D. A. and Stebar, R. F., "Factors Influencing the Effectiveness of Air Injection in Reducing Exhaust Emissions", SAE Progress in Technology, vol. 12, "Vehicle Emissions, Part II", p. 103.

72. Hagan, D. F. and Holiday, G. W., "The Effects of Engine Operation and Design Variables on Exhaust Emissions", SAE Progress in Technology, vol. 6, "Vehicle Emissions", p. 206.

73. Report of the Panel on Electrically Powered Vehicles, "The Automobile and Air Pollution: A Program for Progress", Part II, United States Department of Commerce, December, 1967.

74. Way, G. and Fagley, W. S., "Field Survey of Exhaust Gas Composition", SAE Progress in Technology, vol. 6, "Vehicle Emissions", p. 102.

75. A Progress Report on the Effects of Engine Operating Variables on the Composition of Automotive Exhaust Gases", Coordinating Research Council, Inc., April, 1958.

76. Neerman, J. C. and Millar, G. H., "Determination of Hydrocarbon Emission Rate by Continuous Airflow Measurement and Exhaust Analysis", SAE Progress in Technology, vol. 6, "Vehicle Emissions", p. 70.

77. Engine Performance Specifications, Continental Motors Corporation, received June, 1968.

78. George, R. E. and Burlin, R. M., Air Pollution from Commercial Jet Aircraft in Los Angeles County, Air Pollution Control Division, County of Los Angeles, April, 1960.

79. Smith, D. S., Sawyer, R. F. and Starkman, E. S., "Oxides of Nitrogen from Gas Turbines", APCA Journal, vol. 18, no. 1, January, 1968.

80. Lozano, E. R., Melvin, W. W. and Hochheiser, S., "Air Pollution Emissions from Jet Engines", APCA Journal, vol. 18, no. 6, June, 1968.

81. Aircraft Engine Group, General Electric Company, direct communication, July 30, 1968.

82. Allison Division, General Motors Corporation, direct communication, August 7, 1968.

83. Pratt & Whitney Aircraft Division, United Aircraft Corporation, direct communication, October 3, 1968.

84. Aerospace Industries Association of America, Inc., Letter to National Air Pollution Control Administration, November 26, 1968.

85. Hewson, E., Wendell & Olsson, E. Lars, "Lake Effects on Air Pollution Dispersion", J. Air Pollut. Control Assoc. 17, 11, 757-761, 1967.

86. Panofsky, H. A. and Prasad, B., "The Effect of Meteorological Factors on Air Pollution in a Narrow Valley", J. Appl Meteorol. 6, 493-499, 1967.

87. Flemming, G., "Concerning the Effect of Terrain Configuration on Smoke Dispersal", Atmospheric Environment, 1, 239-252, 1967.

88. Chandler, T. J., "London's Heat Island", Proc. Third International Biometeorological Congress, Ed. by S. W. Tromp and W. H. Weihe, 2, 589-597, Pergamon Press, 1967.

89. Hutcheson, R. J., et. al., "Observations of the Urban Heat Island of a Small City", Amer. Meteorol. Soc. Bull., 48, 1, 79, 1967.

90. Parry, M., "The Urban Heat Island", Proc. Third International Biometeorological Congress, Ed. by S. W. Tromp and W. H. Weihe, vol. 2, Pergamon Press, 1967, pp. 616-624.

91. Landsberg, H. E., "Air Pollution and Urban Climate", Proc. Third International Biometeorological Congress, Ed. by S. W. Tromp and W. H. Weihe, vol. 2, 648-656, 1967.

92. Leighton, P. A., "Geographical Aspects of Air Pollution", The Geographical Review, vol. 61, 151-174, 1966.

93. Lowry, W. P., "The Climate of Cities", Scientific American, 217, 1967.

94. Moroz, W. J. and Hewson, E. W., "The Mesoscale Interaction of a Lake Breeze and Low Level Outflow from a Thunderstorm", J. Appl. Meteorol., 5, 148-155. 1966.

95. Thompson, A. H., "Surface Temperature Inversions in a Canyon", J. Appl. Meteorol., 6, 287-296, 1967.

96. Munn, R. E. and Cole, A. F. W., "Turbulence and Diffusion in the Wake of a Building", Atmospheric Environment, 1, 33-43, 1967.

97. Van der Hoven, "Atmospheric Transport and Diffusion at Coastal Sites", Nuclear Safety, 8, 490-499, 1967.

98. Bornstein, R. D., "Observations of the Urban Heat Island Effect on New York City", J. Appl. Meteorol., 7, 575-582, 1968.

99. Woollum, C. A., "Notes from a Study of the Microclimatology of the Washington, D. C. Area for the Winter and Spring Seasons", Weatherwise, 1964, pp. 263-271.

100. Frizzola, J. A. and Fisher, E. L., "A Series of Sea Breeze Observations in the New York City Area", J. Appl. Meteorol., 2, 722-739, 1963.

101. DeMarrais, G. A., Holaworth, G. C. and Hosler, C. R., "Meteorological Summaries Pertinent to Atmospheric Transport and Dispersion over Southern California", United States Weather Bureau Technical Paper No. 54, Washington, D. C., 1965.

102. Bell, G. G., "Meteorological Effects of California Air Pollution", Proc. Third International Biometeorological Congress, Ed. by S. W. Tromp and W. H. Weihe, 2, 628-640, Pergamon Press, 1967.

103. Frenzel, C. W., "Diurnal Wind Variation in Central California", J. Appl. Meteorol., 1, 405-412, 1962.

104. Lea, D. A., "Vertical Ozone Distribution in the Lower Troposphere Near an Urban Pollution Camplex", J. Appl. Meteorol., 7, 252-257, 1968.

105. Leipper, D. F., "The Sharp Smog Bank and California Fog Development", Amer. Meteorol. Soc. Bull., 49, 4, 354-358, 1968.

106. Fosberg, M. A. and Schroeder, M. J., "Marine Air Penetration of Central California", J. Appl. Meteorol., 5, 573-589, 1966.

107. Schroeder, M. J., et.al., "Marine Air Invasion of the Pacific Coast: A Problem Analysis", Amer. Meteorol. Soc. Bull., 48, 803-808, 1967.

108. Stephens, E. R., "Temperature Inversions and the Trapping of Air Pollutants", Weatherwise, 1965, p. 172.

109. Angell, J. K., et.al., "Tetroon Trajectories in an Urban Atmosphere", J. Appl. Meteorol., 5, 565-572, (oct.).

110. Nicksic, S. W., Harkins, J. and Painter, L. J., "Statistical Survey of Data Relating to Hydrocarbon and Oxides of Nitrogen Relationships in Photochemical Smog", Air & Water Pollut. Int. J., 15-23, 1966.

111. Schuck, E. A., Pitts, J. N. and Wan, J. K. S., "Relationships Between Certain Meteorological Factors and Photochemical Smog", Air & Water Pollut. Int. J., 10, 689-711, 1966.

112. Romanovsky, J. C., Ingels, R. M. and Gordon, R. J., " Estimation of Smog Effects in the Hydrocarbon-Nitric Oxide System", Air Pollut. Assoc. J., 17, 454, 459, 1967.

113. Holzworth, G. C., "Mixing Depths, Wind Speeds and Air Pollution Potential for Selected Locations in the United States", J. Appl. Meteorol., 6, 1039-1044, 1967.

114. Holzworth, G. C., "Large-Scale Influences on Air Pollution", APCA Paper No. 68-52, 1968.

115. Slade, D. H., "Dispersion Estimates from Pollutant Releases of a Few Seconds to 8-Hours in Duration", Technical Note 2-ARL-1, ESSA, United States Department of Commerce, Washington, D. C., August, 1965.

116. Progress in the Prevention and Control of Air Pollution, United States Department of Health, Education and Welfare, June, 1968.

117. Air Pollution Data for Los Angeles County, Air Pollution Control District, County of Los Angeles, January, 1967.

118. Lemke, et.al., Los-Angeles County Government Notebook, Part II, September, 1965, p. 6.

119. Nolan, M., "A Survey of Air Pollution in Communities Around the John F. Kennedy International Airport", Department of Health, Education and Welfare, Public Health Service, Robert A. Taft Sanitary Engineering Center, Cincinatti, Ohio, June, 1966.

120. Hochheizer and Lozano, "Air Pollution Emissions from Jet Aircraft Operating in the New York Metropolitan Area", (SAE Paper No. 680339), April, 1968.

121. Goldsmith, J. R., "Effects of Air Pollution on Human Health", Air Pollution. 2nd. ed., Academic Press, New York, 1968.

122. New York State Department of Health, Ambient Air Quality Objectives --Classifications Systems, New York State Air Pollution Control Board, 1964.

123. McDonald, J. E., "Visibility Reduction Due to Jet-Exhaust Carbon Particles", J. Appl. Meteorol., 1, 1962.

124. Johnson, H. C. and Flynn, N. E., "Report on Automobile, Diesel, Railroad, Aircraft and Ship Emissions in the Bay Area Air Pollution Control District", Bay Area Air Pollution Control District, 1964.

125. United States Department of Commerce, The Automobile & Air Pollution: A Program for Progress, Pt. II, Washington, D. C., December, 1967.

126. United States Department of Health, Education and Welfare, Public Health Service, "New York - New Jersey Air Pollution Abatement Activity -- Sulfur Compounds and Carbon Monoxide", Cincinatti, Ohio, January, 1967.

127. United States Department of Health, Education and Welfare, Public Health Service, "New York - New Jersey Air Pollution Abatement Activity -- Phase II - Particulate Matter", Cincinatti, Ohio, December, 1967.

128. United States Department of Health, Education and Welfare, Public Health Service, National Center for Air Pollution Control, "Washington, D. C. Metropolitan Area Air Pollution Abatement Activity", Cincinatti, Ohio, 1967.

129. Air Transport Association and Aerospace Industries Association, Summary Status Report on Aircraft Engine Exhaust Emissions, September, 1968.

130. Toone, B., "A Review of Aero Engine Smoke Emission", Cranfield International Propulsion Symposium, The College of Aeronautics, Cranfield, Bedford, England, 1967.

131. Fiorello, S. C., The Navy's Smoke Abatement Program, (SAE Paper No. 680345), Society of Automotive Engineers, Air Transportation Meeting, New York, April, 1968.

132. The Design and Performance Analysis of Gas Turbine Combustion Chambers (NREC Report No. 1082), Northern Research and Engineering Corporation, Cambridge, Massachusetts, December, 1964.

133. McDonald, J. E., "Visibility Reduction due to Jet-Exhaust Carbon Particles", J. Appl. Meteorol., 1, 391-398, 1962.

134. Engen, T., "Man's Ability to Preceive Odors", Paper at Symposium on "Communication by Chemical Signals", Clark University, Worcester, Massachusetts, June, 1968.

135. Bolt Beranek and Newman, Inc., "A Study--Insulating Houses from Aircraft Noise", 1966.

136. New York State Air Pollution Control Board, Ambient Air Quality Standards, November 3, 1968.

TABLES

TABLE 1 - AIRCRAFT CLASSIFICATION SYSTEM FOR ASSESSING EXHAUST EMISSIONS

Aircraft class	Aircraft type	Examples	Representative engine		
			Manufacturer and model	Type	Maximum thrust or power
1	Long-range jet transport	Boeing 707 Douglas DC-8	Pratt & Whitney JT3D	Turbofan	18,000 lb-t
2	Medium-range jet transport	Boeing 727 Douglas DC-9	Pratt & Whitney JT8D	Turbofan	14,000 lb-t
3	Business jet	Lockheed Jetstar North American Sabreliner	Pratt & Whitney JT12	Turbojet	3,000 lb-t
4	Turboprop transport	Lockheed Electra Fairchild Hiller FH-227	Allison 501-D13	Turboprop	3,750 eshp*
5	Piston-engine transport	Douglas DC-6 Convair 440	Pratt & Whitney R-2800	Radial piston	2,500 hp
6	Piston-engine utility	Cessna 210 Centurion Piper 32-300 Cherokee Six	Continental 10-520-A	Opposed piston	285 hp
7	Turbine-engine helicopter	Sikorsky S-61 Vertol 107	General Electric CT58	Turboshaft	1,400 hp

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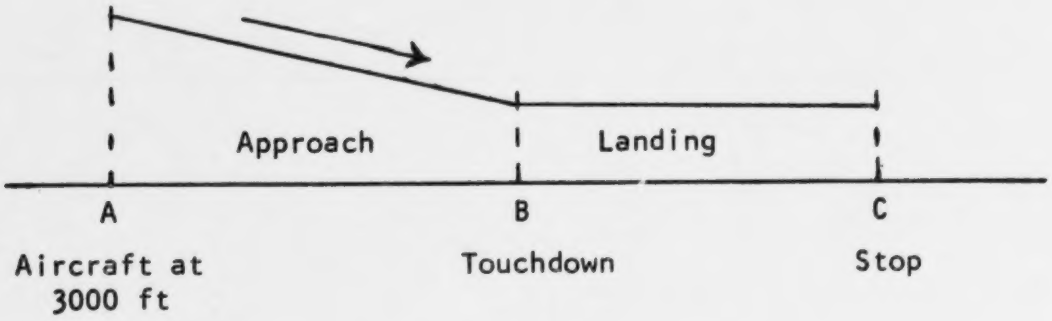
*eshp = equivalent shaft horsepower

TABLE 2 - AIRCRAFT PERFORMANCE CHARACTERISTICS DURING LANDING AND TAKE-OFF OPERATIONS

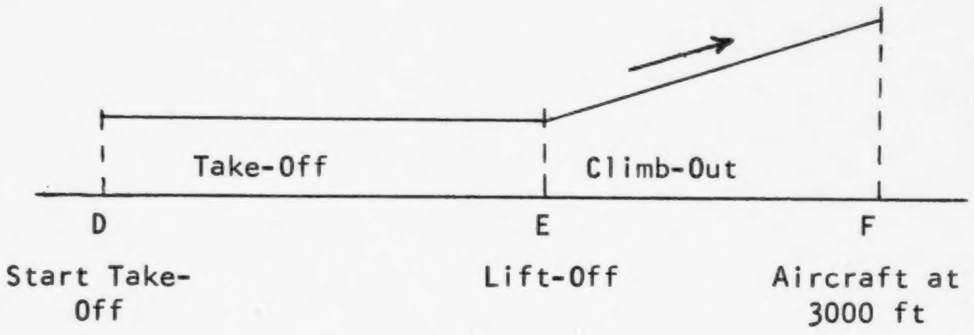


S_{AB}	Distance A to B	S_{BC}	Distance B to C
V_{AB}	Average Velocity A to B	V_B	Touchdown Velocity
t_{AB}	Time to Travel A to B	t_{BC}	Time to Travel B to C

Class	S_{AB} Miles	V_{AB} fps	t_{AB} min	S_{BC} feet	V_B fps	t_{BC} min
1	9.4	230	3.6	2800	227	0.4
2	9.0	264	3.0	1900	213	0.3
3	6.0	330	1.6	1900	147	0.4
4	10.3	202	4.5	1700	191	0.3
5	9.0	172	4.6	2330	135	0.6
6	5.0	117	3.8	1000	100	0.3
7	15.0	200	6.5	0	0	0

Durations of idle and taxi modes assumed to be 1 and 12 minutes respectively for classes 1 through 6, and 1 and 6 minutes for class 7 (helicopters).

TABLE 2 - AIRCRAFT PERFORMANCE CHARACTERISTICS DURING LANDING AND TAKE-OFF OPERATIONS (CONTINUED)


Take-Off
Climb-Out
D
E
F
Start Take-Off
Lift-Off
Aircraft at 3000 ft

S_{DE}	Distance D to E	S_{EF}	Distance E to F
V_E	Velocity at E	V_{EF}	Average Velocity E to F
t_{DE}	Time to Travel D to E	t_{EF}	Time to Travel E to F

Class	S_{DE} feet	V_E fps	t_{DE} mins	S_{EF} miles	V_{EF} fps	t_{EF} mins
1	9300	305	1.0	8.1	320	2.2
2	6075	265	0.8	6.5	300	1.9
3	2800	235	0.4	1.6	285	0.5
4	3280	178	0.6	10.6	260	3.6
5	3150	187	0.6	14.8	260	5.0
6	1545	120	0.4	6.3	220	2.5
7	0	0	0	15.0	200	6.5

Assumed Conditions:
(a) Runway at sea level
(b) Zero runway slope
(c) Temperature 60 deg F
(d) Zero wind
(e) Aircraft at maximum load

TABLE 3 - AIRCRAFT REGISTERED WITH FAA BY TYPE: JANUARY 1, 1967

Type of aircraft	Total	Eligible	Ineligible
Total	155,132	107,085	48,047
Fixed-wing airplane	150,948	104,556	46,392
Turbojet	1,547	1,423	124
1-engine	69	6	63
2-engine	513	462	51
3-engine	287	287	--
4-engine	678	668	10
Turboprop	904	863	41
1-engine	42	40	2
2-engine	618	583	35
4-engine	244	240	4
Piston	148,497	102,270	46,227
1-engine	130,723	88,653	42,070
100 hp and less	42,186	23,543	18,643
101-200 hp	50,292	36,942	13,350
201-350 hp	32,965	25,997	6,968
351-500 hp	3,273	1,387	1,886
501-700 hp	915	429	486
Over 700 hp	1,092	355	737
2-engine	16,895	13,010	3,885
800 hp and less	12,099	9,984	2,115
801-2,000 hp	2,341	1,527	814
2,001-4,000 hp	1,284	823	461
Over 4,000 hp	1,171	676	495
3-engine	29	9	20
1,000 hp and less	6	5	1
Over 1,000 hp	23	4	19
4-engine	850	598	252
5,000 hp and less	36	18	18
5,001-6,000 hp	95	27	68
6,001-10,000 hp	318	263	55
Over 10,000 hp	401	290	111
Rotorcraft	2,740	1,652	1,088
Turbine	126	88	38
Piston	2,614	1,564	1,050
Gliders	1,348	841	507
Blimps	6	2	4
Balloons	90	34	56

Source: Reference 14

TABLE 4 - U. S. POPULATION OF ACTIVE, CIVIL AIRCRAFT, PAST AND FUTURE

Year (As of Jan 1)	Total Active Aircraft	Fixed-Wing Aircraft			Rotor-craft	Other
		Total Fixed-Wing	Turbine	Piston		
1960	70,747	69,681	377	69,304	543	523
1961	78,760	77,730	546	77,184	659	371
1962	82,853	81,603	748	80,855	823	427
1963	86,287	84,795	851	83,944	985	507
1964	87,267	85,541	972	84,569	1,138	588
1965	90,935	88,962	1,118	87,844	1,325	648
1966	97,741	95,407	1,624	93,783	1,525	809
1967	107,085	104,556	2,285	102,270	1,652	877
1968*	114,400	111,700	3,000	108,700	1,750	950
1969*	122,600	119,600	3,800	115,800	2,000	1,000
1970*	130,600	127,400	4,400	123,000	2,200	1,000
1971*	138,900	135,400	5,000	130,400	2,400	1,100
1972*	146,900	143,200	5,500	137,700	2,600	1,100
1973*	155,100	151,100	6,200	144,900	2,800	1,200
1974*	163,100	158,900	6,900	152,100	3,000	1,200
1979*	206,900	201,200	10,700	190,500	4,200	1,500

*Estimated

Sources: References 14 and 16

TABLE 5 - ACTIVE, CIVIL AIRCRAFT BY YEAR OF MANUFACTURE AS OF JANUARY 1, 1967

Year of Manufacture	Number of Aircraft	Per Cent of Total
1966	11,893	11.1
1965	9,388	8.8
1964	7,200	6.7
1963	5,544	5.2
1962	4,769	4.5
1961	4,586	4.3
1960	5,161	4.8
1959	5,671	5.3
1958	4,421	4.1
1957	3,686	3.4
1956 and prior years	44,766	41.8
Total	107,085	100.0

Source: Reference 14

TABLE 6 - COMPOSITION OF THE U. S. AIR CARRIER FLEET, PAST AND FUTURE

Year (As of Jan. 1)	Total Aircraft	Fixed-Wing Aircraft				Rotorcraft	
		Total	Piston	Turboprop	Turbojet and Fan	Piston	Turbine
1960	2,135	2,112	1,812	216	84	23	0
1961	2,135	2,110	1,678	230	202	24	1
1962	2,104	2,085	1,505	261	319	19	0
1963	2,047	2,027	1,368	262	397	12	8
1964	2,079	2,059	1,360	267	432	8	12
1965	2,081	2,061	1,221	276	564	7	13
1966	2,125	2,104	1,067	312	725	6	15
1967	2,272	2,251	873	372	1,006	5	16
1968	2,452	2,430	642	444	1,344	5	17
1969*	2,583	2,561	368	407	1,786	5	17
1970*	2,730	2,704	287	430	1,987	5	21
1971*	2,860	2,834	260	405	2,169	5	21
1972*	2,990	2,962	240	404	2,318	5	23
1973*	3,170	3,141	223	396	2,522	5	24
1974*	3,320	3,290	201	393	2,696	5	25
1979*	3,860	3,820	151	380	3,289	0	40

*Estimates

Sources: References 14 and 16

TABLE 7 - AIRCRAFT OF THE U. S. AIR CARRIER FLEET (JANUARY 1968)

Fixed-Wing Aircraft - Turbine

Aircraft Manufacturer	Aircraft Model Series	Engine Number and Model	Number Aircraft in Service
Boeing Company	707	4 PW JT3C, JT3D, JT4A	338
	720	4 PW JT3C, JT3D	135
	727	3 PW JT8D	410
British Aircraft Corporation	111	2 RR Spey 506, 510	57
	V-745	4 RR Dart 510	38
Canadair	CL-44D	4 RR Tyne 515	19
Convair	240T (600)	2 RR Dart 542	29
	340T (580)	2 Al 501-D13	77
	340T (640)	2 RR Dart 542	8
	880	4 GE CJ805-3	45
	990	4 GE CJ805-23	14
Dassault-Sud	SE-20	2 GE CF700	3
DeHavilland of Canada	Twin Otter	2 UAC PT6A-20	3
Fairchild Hiller	F-27	2 RR Dart 511, 528, 532	49
	FH-227	2 RR Dart 532	58
Grumman	159	2 RR Dart 529	2
Hawker-Siddeley	650	4 RR Dart 526	5
Lockheed	100	4 Al 501-D22	9
	188	4 Al 501-D13	125
	1329	4 PW JT12A	1
Douglas	DC-8	4 PW JT3C, JT3D, JT4A	173
	DC-9	2 PW JT8D	148
Nihon	YS-11	2 RR Dart 542	2
Nord	262	2 Tu Bastan VIC	12
Pilatus	PC-6A	1 Tu Astazou XII	3
	PC-6B	1 UAC PT6A-20	4

TABLE 7 - AIRCRAFT OF THE U. S. AIR CARRIER FLEET (JANUARY 1968) (CONTINUED)

Aircraft Manufacturer	Aircraft Model Series	Engine Number and Model	Number Aircraft in Service
Short	SC-7	2 Tu Astazou XII	1
Sud	Caravelle	2 RR Avon 532R	20

Fixed-Wing Aircraft - Piston

Aircraft Manufacturer	Aircraft Model Series	Engine Number and Model	Number Aircraft in Service
Aero Commander	680E	2 Ly IGSO-540	1
Convair	240	2 PW R2800	12
	340/440	2 PW R2800	78
	28-5ACF	2 PW R1830	4
Curtis	C-46, 20T	2 PW R2800	63
Douglas	DC-3, 3A	2 PW R1830	107
	DC-4	4 PW R2000	10
	DC-6	4 PW R2800	133
	DC-7	4 Wr R3350	55
Fairchild	C-82	2 PW R2800	4
Grumman	21, 21A	2 PW R985	18
	44A	2 Ly 0-435	2
	73	2 PW R-1340	2
	SA 16	2 Wr R1820	2
Lockheed	12	2 PW R985	1
	049/149	4 Wr R3350	5
	749	4 Wr R3350	7
	1049	4 Wr R3350	54
	1649	4 Wr R3350	1
Martin	202A	2 PW R2800	2
	404	2 PW R2800	57
Piper	31	2 Ly TIO-540	4
	18	1 Ly 0-320	3
Cessna	180/185	1 Co 0-470	10
	206	1 Co IO-520	1

TABLE 7 - AIRCRAFT OF THE U. S. AIR CARRIER FLEET (JANUARY 1968) (CONTINUED)

Aircraft Manufacturer	Aircraft Model Series	Engine Number and Model	Number Aircraft in Service
DeHavilland of Canada	DHC-2	1 PW R-985	3
Pilatus	PC-6	1 Ly GSO-480	3

Rotorcraft - Turbine

Aircraft Manufacturer	Aircraft Model Series	Engine Number and Model	Number Aircraft in Service
Sikorsky	S-61	2 GE CT58	9
	S-62	1 GE CT58	1
Vertol	107-II	2 GE CT58	7

Rotorcraft - Piston

Aircraft Manufacturer	Aircraft Model Series	Engine Number and Model	Number Aircraft in Service
Sikorsky	S-55	1 PW R1340	2
	S-58C	1 Wr R1820	3

Sources: References 6, 14, 17, 18, 19, and 20

TABLE 8 - U. S. AIR CARRIER BY COUNTRY OF MANUFACTURE JANUARY 1968

Country	Number of Aircraft			
	Fixed Wing		Rotorcraft	Total
	Turbine	Piston		
U.S.A.	1621	636	22	2279
Canada	22	3	0	25
Great Britain	101	0	0	101
France	35	0	0	35
Japan	2	0	0	2
Switzerland	7	3	0	10
Total	1788	642	22	2452

Sources: References 14 and 17

TABLE 9 - COMPOSITION OF THE U. S. GENERAL AVIATION FLEET, PAST AND FUTURE

Year (Jan.1)	Total Aircraft	Fixed-Wing Aircraft			Rotor Craft	Other
		Single-Engine Piston	Multiengine Piston	Turbine		
1960	68,727	61,844	5,957	77	525	324
1961	76,549	68,301	7,129	114	634	371
1962	80,632	71,006	8,241	160	798	427
1963	84,121	73,456	8,978	213	967	507
1964	85,088	73,626	9,458	245	1171	588
1965	88,742	76,136	10,346	306	1306	648
1966	95,442	81,134	11,422	574	1503	809
1967	104,706	88,621	12,671	915	1622	877
1968*	112,000	94,500	13,600	1220	1730	950
1969*	120,000	100,400	15,000	1600	2000	1000
1970*	128,000	106,500	16,250	2000	2200	1050
1971*	136,000	112,600	17,500	2400	2400	1100
1972*	144,000	118,700	18,750	2800	2600	1150
1973*	152,000	124,700	20,000	3300	2800	1200
1974*	160,000	130,700	21,200	3850	3000	1250
1979*	203,000	163,800	26,500	7000	4200	1500

*Estimates
Sources: References 14 and 16

TABLE 10 - ACTIVE, GENERAL AVIATION AIRCRAFT BY TYPE

Aircraft Type	Aircraft (Jan. 1967)		Hours Flown (1966)	
	Number	Per cent	Number (000)	Per cent
Total, all types	104,706	100.0	21,023	100.0
Fixed-Wing, Total	102,207	97.8	20,463	97.4
Fixed-Wing, Piston	101,292	96.9	20,040	95.3
Single-Engine, 1-3 places	35,681	34.1	5,847	27.8
100HP or less	26,753	25.6	4,394	20.9
Over 100 HP	8,928	8.5	1,453	6.9
Single-Engine, 4 or more places	52,940	50.5	10,335	49.1
200 HP or less	27,907	26.7	5,751	27.3
Over 200 HP	25,033	23.9	4,584	21.8
Multiengine	12,671	12.1	3,858	18.3
800 HP or less	9,957	9.5	2,748	13.1
801-2000 HP	1,531	1.5	602	2.9
Over 2000 HP	1,183	1.1	508	2.4
Fixed-Wing Turbine	915	0.9	423	2.0
Single-Engine	38	-	NA	-
Multiengine	877	0.8	NA	-
Rotorcraft	1622	1.5	492	2.3
Gliders, balloons, etc.	877	0.8	68	0.3

Source: Reference 14

TABLE 11 - U. S. DEPARTMENT OF DEFENSE INVENTORY OF ACTIVE AIRCRAFT

Service	No. of Active Aircraft		
	July 1, 1967	Jan. 1, 1968	July 1, 1968 (Estimated)
Army	9,375	9,803	10,671
Navy	8,417	8,603	8,942
Air Force	15,017	15,343	15,127
DOD Total	32,809	33,749	34,740

Sources: References 17 and 23

TABLE 12 - TURBINE ENGINES IN THE U. S. AIR CARRIER FLEET (JANUARY 1968)

Manufacturer	Model	Type	Max. Power or Thrust	Number in Use
Allison Division General Motors Corp.	501-D13	Turboprop	3750 eshp	654
	501-D22	Turboprop	4050 eshp	36
General Electric Co.	CJ805-3	Turbojet	11,650 lb-t	180
	CJ805-23	Turbofan	16,100 lb-t	56
	CT58-110/140	Turboshaft	1250/1400 shp	33
	CF700	Turbofan	4125 lb-t	6
Pratt & Whitney Aircraft Division	JT3C-6/7	Turbojet	13,500/12,000 lb-t	160
United Aircraft Corp.	JT3D-1/3	Turbofan	17,000/18,000 lb-t	2048
	JT4A-9/11	Turbojet	16,800/17,500 lb-t	376
	JT8D-1,5,7,9	Turbofan	12,250-14,500 lb-t	1526
	JT12A	Turbojet	3000 lb-t	4
Rolls-Royce Ltd.	Avon 29	Turbojet	12,080 lb-t	40
	Dart 6,7,10	Turboprop	1670-3025 eshp	468
	Spey 3/4	Turbofan	10,410/11,000 lb-t	114
	Tyne 12	Turboprop	5500 eshp	76
Societe Turbomeca	Astazou XII	Turboprop	731 eshp	3
	Bastan VIc	Turboprop	1065 eshp	24
United Aircraft of Canada	PT6A-20	Turboprop	579 eshp	10
Total Engines				5814

Sources: References 6, 19 and 24

TABLE 13 - PISTON ENGINES IN THE U. S. AIR CARRIER FLEET, JANUARY 1968

Manufacturer	Model Series	Type	Max. Power	No. in Use
Avco Lycoming Div. Avco Corp.	0-320	Opposed	150 HP	3
	0-435	Opposed	260 HP	4
	GS0-480	Opposed	270 HP	3
	IGS0-540	Opposed	380 HP	2
	TI0-540	Opposed	310 HP	8
Continental Motors Corp.	0-470	Opposed	225 HP	10
	I0-520	Opposed	285 HP	1
Pratt & Whitney Aircraft Div., United Aircraft Corp.	R-985	Radial	450 HP	41
	R-1340	Radial	600 HP	5
	R-1830	Radial	1200 HP	218
	R-2000	Radial	1450 HP	40
	R-2800	Radial	2400 HP	964
Wright Aeronautical Div., Curtiss-Wright Corp.	R-1820	Radial	1425 HP	7
	R-3350	Radial	2700+ HP	488
Total Engines				1804

Sources: References 6, 18, 19 and 20

TABLE 14 - AIRCRAFT PRODUCTION IN THE UNITED STATES

Calendar Year	Commercial Transport Aircraft	Commercial Rotorcraft	General Aviation Aircraft	Military Aircraft & Rotorcraft	Total Aircraft
1963	100	411	7644	1970	10,125
1964	163	450	9440	2439	12,492
1965	233	388	11,922	2806	15,349
1966	344	390	15,543	3600^E	19,877^E
1967	480	455	13,725	4000^E	18,660^E
1968	555*	500*	14,900*		
1969	430*	17,000*			
1970	275*	18,600*			
1971	240*	20,200*			
1972	230*	21,800*			
1973	225*	23,400*			
1974	215*	25,000*			
1979	280*	32,200*			

E - Estimate * Forecast

Sources: References 16 and 17

TABLE 15 - MAJOR UNITED STATES MANUFACTURERS OF CIVIL AIRCRAFT

Commercial transport	
Manufacturer	1967 Production
Boeing	237
Douglas	196
Fairchild Hiller	38
Lockheed	9
Total	480

Rotorcraft	
Manufacturer	1967 Production
Bell	316
Brantley	17
Enstrom	7
Fairchild Hiller	53
Hughes	48
Sikorsky	14
Total	455

General aviation	
Manufacturer	1967 Production
Alon	50
Beech	1,260
Bellanca	86
Cessna	6,233
Champion	267
Grumman	52
Lake	15
Lear	34
Lockheed	19
Maule	43
Mooney	642
North American	386
Piper	4,490
Other	148
Total	13,725

Total 1967 production, all categories - 14,660

Source: Reference 17

TABLE 16 - FOREIGN-MADE AIRCRAFT DELIVERED TO U. S. CUSTOMERS

Manufacturer	Aircraft	Engines	Engine Type	Aircraft Deliveries Through 1967
Aermacchi	AL-60	1 Ly. IO-720	Piston	6
Beagle	B-206-2	2 RR-Con.	Piston	14
British Aircraft Corp.	BAC-111	2 RR Spey	Turbofan	62
	Viscount	4 RR Dart	Turboprop	92
Britten-Norman	BN-2	1 Ly.O-540	Piston	52
Canadair	CL-44D	4 RR Tyne	Turboprop	24
Dassault-Sud	SE-20	2 GE CF700	Turbofan	80
DeHavilland, Canada	Twin Otter	2 UAC PT-6A-20	Turboprop	52
	DHC-2	1 PW R-985	Piston	67
DeHavilland, G. B.	DH-104	2 DeH.	Piston	86
Dornier	DO28-A1	1 Ly. O-540	Piston	6
ndley-Page	Herald 200	2 RR Dart	Turboprop	3
	137	2 Tu Astazou	Turboprop	1
Hawker-Siddeley	101	4 RR Dart	Turboprop	7
	HS 125	2 RR Viper	Turbojet	61
	Dove	2 RR Gipsy	Piston	62
	Heron	4 RR Gipsy	Piston	3
Mitsubishi	MU-2	Tu or AR	Turboprop	1
Nihon	YS-11	2 RR Dart	Turboprop	10
Nord	262	2 Tu Bastan	Turboprop	13
Pilatus	PC-6A	1 Tu, Astazou	Turboprop	21
	PC-6B	1 UAC PT6A	Turboprop	4
	PC-6	1 Ly. GSO-480	Piston	5
Short	SC7	2 Tu Astazou	Turboprop	5
Sud	Caravelle	2 RR Avon	Turbojet	21

Note: List not complete and numbers are approximate.

Sources: References 6, 20, 22, 24, 25, 26 and direct correspondence with manufacturers.

TABLE 17 - AIRCRAFT ENGINE PRODUCTION IN THE UNITED STATES

Calendar Year	Civil Aircraft Engines		Military Aircraft Engines		Total
	Piston	Turbine	Piston	Turbine	
1963	11,322	473	155	5,235	17,185
1964	13,346	859	175	5,205	19,585
1965	17,018	1,169	92	5,099	23,378
1966	21,324	1,938	75^E	$6,000^E$	$29,337^E$
1967	18,100	2,624	75^E	$6,450^E$	$26,747^E$
1968	20,600*	2,700*			
1969	23,000*	2,300*			
1970	25,200*	1,700*			
1971	26,500*	1,600*			
1972	29,700*	1,650*			
1973	31,800*	1,650*			
1974	33,900*	1,650*			
1979	43,900*	2,400*			

E - Estimate   * Forecast

Sources: References 16, 17 and 27

TABLE 18 - MAJOR UNITED STATES AIRCRAFT ENGINE MANUFACTURERS

Manufacturer	Engine types	1967 Production civil aircraft engines
Continental Motors Corp.	Piston	7,845
General Electric Co.	Turbine	260
Lycoming Division Avco Corporation	Piston	9,841
Pratt & Whitney Aircraft Division United Aircraft Corp.	Turbine	2,276
Other[a]	Piston and Turbine	502
Total		20,724

Sources: References 17 and 27

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[a] Includes: Allison Division, General Motors Corp.
AiResearch Manufacturing Co., Garrett Corp.
Franklin Engine Co., Inc.
Wright Aeronautical Division, Curtiss-Wright Corp.

TABLE 19 - FOREIGN MANUFACTURERS OF AIRCRAFT ENGINES SOLD TO U. S. CIVIL AIRCRAFT MANUFACTURERS

Engine Manufacturer	Engine Type	Sales to U.S. Parties Through Sept. 1968
Rolls-Royce Ltd., England	Turboprop Turbofan	877 352
United Aircraft of Canada Ltd., Div. United Aircraft Corp.	Turboprop	893

Sources: References 26 and 28

TABLE 20 - ANNUAL U. S. AIR TERMINAL TRAFFIC ACTIVITY (LANDING-TAKE-OFF CYCLES - MILLIONS)

Calendar Year	Total Civil Activity	Air Carrier Activity	General Aviation Activity	Military	
				FAA-Controlled Terminals	Military Terminals
1960	11.0	3.6	7.4	1.9	
1961	11.3	3.5	7.8	1.9	
1962	12.2	3.5	8.7	1.9	
1963	13.7	3.7	10.0	1.9	
1964	15.2	3.7	11.5	1.9	
1965	17.2	3.9	13.3	1.7	9.1
1966	20.8	4.1	16.7	1.7	12.3
1967	23.3	4.7	18.6	1.7	14.8
1968*	27.0	5.3	21.7		
1969*	30.8	5.9	24.9		
1970*	34.1	6.3	27.8		
1971*	38.0	6.7	31.3		
1972*	42.4	7.2	35.2		
1973*	47.1	7.6	39.5		
1974*	52.0	8.0	44.0		
1979*	82.5	10.3	72.2		

* Projections

Sources: References 16, 29 and 30

TABLE 21 - 1967 AIR TRAFFIC ACTIVITY AT MAJOR AIR TERMINALS IN THE NEW YORK CITY METROPOLITAN AREA (LANDING-TAKE-OFF CYCLES - THOUSANDS)

Terminal*	Total Cycles	Air Carrier	General Aviation			Military		
			Total	Itinerant	Local	Total	Itinerant	Local
J. F. Kennedy	241	202	38	38	0	1	1	0
Laguardia	165	103	61	60	1	1	1	0
Newark	130	97	33	33	0	0	0	0
Teterboro	144	3	141	62	79	0	0	0
Naval Air Station	23	0	2	0	2	21	4	17
Bridgeport	101	3	95	45	50	3	1	2
Morristown	86	1	85	45	40	0	0	0
White Plains	125	3	121	66	55	1	1	0
Total	1015	412	576	349	227	27	8	19

Sources: References 29 and 30

* Includes FAA-controlled terminals and military terminals in the New York Interstate Air Quality Control Region.

TABLE 22 - 1967 AIR TRAFFIC ACTIVITY AT MAJOR AIR TERMINALS IN THE WASHINGTON, D. C., METROPOLITAN AREA (LANDING-TAKE-OFF CYCLES - THOUSANDS)

Terminal*	Total Cycles	Air Carrier	General Aviation			Military		
			Total	Itinerant	Local	Total	Itinerant	Local
National	167	119	46	45	1	2	2	0
Dulles	106	25	47	21	26	34	7	27
Pentagon	4	0	0	0	0	4	4	0
Andrews AFB	104	0	1	0	1	103	60	43
Quantico MCAS	19	0	6	0	6	13	2	11
Ft. Belvoir	40	0	0	0	0	40	7	33
Total	440	144	100	66	34	196	82	114

Sources: References 29 and 30

* Includes FAA-controlled terminals and active military terminals in the National Capitol Interstate Air Quality Control Region.

TABLE 23 - 1967 AIR TRAFFIC ACTIVITY AT AIR TERMINALS IN THE LOS ANGELES METROPOLITAN AREA (LANDING-TAKE-OFF CYCLES - THOUSANDS)

Terminal	Total Cycles	Air Carrier	General Aviation			Military		
			Total	Itinerant	Local	Total	Itinerant	Local
Los Angeles	241	192	44	39	5	5	5	0
Long Beach	242	3	225	119	106	14	3	11
Van Nuys	248	2	244	135	109	2	2	0
Santa Monica	178	1	177	69	108	0	0	0
La Verne (Brackett)	109	0	109	54	55	0	0	0
Burbank	119	9	109	72	37	1	1	0
Hawthorne	148	0	148	76	72	0	0	0
Torrance	186	0	185	65	120	1	0	1
Palmdale	59	0	31	8	23	28	6	22
Non-FAA Terminals	285	0	285	NA	NA	0	0	0
Total	1815	207	1557			51	17	34

Sources: References 3, 29, and 30

TABLE 24 - AIRCRAFT ACTIVITY LEVELS BY AIRCRAFT CLASS AT VARIOUS TERMINALS AND METROPOLITAN AREAS

	Average Number of LTO Cycles Per Day in 1967[b]							
	Aircraft Class							
Area	1	2	3	4	5	6	7	Total
J. F. Kennedy Terminal	256 (4.0)	183 (3.0)	1 (c)	49 (3.5)	13 (3.1)	105 (1.4)	53 (2.0)	660
Teterboro Terminal	0	0	0	0	0	395 (1.4)	0	395
New York IAQCR[a]	303 (4.0)	459 (2.8)	37 (c)	178 (3.1)	61 (3.3)	1624 (1.4)	118 (2.0)	2784
Washington National Terminal	3 (4.0)	132 (2.6)	3 (c)	123 (3.3)	69 (3.0)	127 (1.4)	0	457
National capital IAQCR[a]	37 (4.0)	155 (2.7)	265 (c)	208 (3.2)	126 (3.1)	380 (1.4)	26 (2.0)	1197
Los Angeles International Terminal	263 (4.0)	156 (2.9)	7 (c)	45 (2.9)	17 (3.2)	126 (1.4)	46 (2.0)	660
Long Beach Terminal	0	0	19 (c)	6	4	623	2	654
Los Angeles County	276 (4.0)	181 (3.0)	70 (c)	69 (3.0)	29 (3.1)	4286 (1.4)	54 (2.0)	4967
Total nation (FAA-controlled terminals)	2444 (4.0)	4202 (2.7)	2300 (c)	4203 (2.8)	2820 (3.0)	52091 (1.4)	615 (2.0)	68675

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[a] IAQCR = Interstate air quality control region

[b] Numbers in parentheses are average numbers of engine per aircraft.

[c] Class 3 activity at these terminals is mostly military aircraft. Military engine estimated to be equivalent to six civil aircraft engines used in class 3 aircraft.

TABLE 25 - 1967 AIR TRAFFIC ACTIVITY RATES AT MAJOR AIR TERMINALS IN THE NEW YORK CITY METROPOLITAN AREA

Terminal	Daily Rate (LTO Cycles/Day)		Hourly Rate (LTO Cycles/Hour)	
	Average	Peak*	Average	Peak*
J. F. Kennedy	660	810	27.5	75
Laguardia	452	760	18.8	79
Newark	356	507	14.8	45
Teterboro	395	720	16.4	92
Naval Air Station	63	NA	2.6	NA
Bridgeport	277	822	11.5	94
Morristown	236	582	9.8	62
White Plains	342	770	14.3	68

*Estimates based upon 1965 peak-average ratios

Sources: References 29, 30, and 34

TABLE 26 - 1967 AIR TRAFFIC ACTIVITY RATES AT MAJOR AIR TERMINALS IN THE WASHINGTON, D. C., METROPOLITAN AREA

Terminal	Daily Rate (LTO Cycles/Day)		Hourly Rate (LTO Cycles/Hour)	
	Average	Peak*	Average	Peak*
National	457	620	19.1	60
Dulles	291	595	12.1	109
Pentagon	10	NA	0.4	NA
Andrews Air Force Base	286	540	11.0	97
Quantico MCAS	52	NA	2.2	NA
Fort Belvoir	110	NA	4.6	NA

*Estimates based upon 1965 peak-average ratios

Sources: References 29, 30, and 34

TABLE 27 - 1967 AIR TRAFFIC ACTIVITY RATES AT AIR TERMINALS IN LOS ANGELES COUNTY

Terminal	Daily Rate (LTO Cycles/Day)		Hourly Rate (LTO Cycles/Hour)	
	Average	Peak*	Average	Peak*
Los Angeles	660	1160	27.5	94
Long Beach	654	1305	27.7	160
Van Nuys	680	1515	28.4	157
Santa Monica	488	1020	20.3	94
La Verne (Brackett)	295	NA	12.5	NA
Burbank	325	535	13.5	111
Hawthorne	408	615	17.0	66
Torrance	510	1455	21.2	99
Palmdale	162	423	6.7	104
Non-FAA Terminals	780	NA	32.6	NA

*Estimates based upon 1965 peak-average ratios

Sources: References 3, 29, 30, and 34

TABLE 28 - SCHEDULED AIR CARRIER AND AIR TAXI ARRIVALS AT J. F. KENNEDY INTERNATIONAL TERMINAL MAY 1, 1968

Aircraft Class	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
1	9	3	4	6	2	2	15	4	8	6	9	8
2	4	8	4	1	2	4	3	5	9	3	7	7
4	-	-	-	-	-	1		2	2	2	2	4
5	1	-	-	-	-	-	-	-	1	-	-	-
6	-	-	-	-	-	-	1	4	4	1	4	4
7	-	-	-	-	-	-	-	3	3	5	3	3

Aircraft Class	Hour												Daily Total
	13	14	15	16	17	18	19	20	21	22	23	24	
1	13	17	14	21	29	36	21	19	22	19	15	8	310
2	8	8	9	17	14	14	11	8	11	9	7	-	173
4	2	2	-	2	4	1	3	3	1	3	3	2	39
5	-	-	1	-	-	-	1	-	-	-	-	-	4
6	3	3	6	2	4	4	6	4	5	3	2	-	60
7	5	5	6	7	7	5	9	6	3	4	2	-	76
Total Scheduled Arrivals													622

Sources: References 35 and 36

TABLE 29 - SCHEDULED AIR CARRIER AND AIR TAXI ARRIVALS BY AIRCRAFT TYPE, MAY 1, 1968 WASHINGTON NATIONAL TERMINAL

Aircraft Class	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
1	-	-	-	-	-	-	-	-	-	1	-	-
2	-	-	-	-	-	-	-	9	17	10	14	11
4	1	1	-	1	-	-	1	1	2	5	5	3
5	-	2	-	-	-	-	-	-	3	4	4	1
6	-	-	-	-	-	-	-	3	4	1	1	-
7	-	-	-	-	-	-	-	-	-	-	-	-

Aircraft Class	Hour												Daily Total
	13	14	15	16	17	18	19	20	21	22	23	24	
1	-	-	-	-	-	-	-	1	-	-	1	-	3
2	11	12	11	14	13	10	13	13	14	16	6	1	195
4	4	4	8	5	4	5	3	5	5	3	6	2	74
5	3	5	2	4	1	4	3	2	5	3	4	1	51
6	1	-	-	-	3	5	1	1	2	-	-	-	22
7	-	-	-	-	-	-	-	-	-	-	-	-	0
Total Scheduled Arrivals													345

Sources: References 35 and 36

TABLE 30 - SCHEDULED AIR CARRIER AND AIR TAXI ARRIVALS BY AIRCRAFT TYPE, MAY 1, 1968 LOS ANGELES INTERNATIONAL TERMINAL

Aircraft Class	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
1	6	5	4	3	5	1	4	5	12	8	26	20
2	-	-	-	2	3	1	4	7	9	11	16	11
4	1	-	-	-	-	1	2	4	2	5	6	1
5	-	-	-	-	-	-	-	1	1	-	1	1
6	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	-	2	3	5	2	3	5

Aircraft Class	Hour												Daily Total
	13	14	15	16	17	18	19	20	21	22	23	24	
1	12	10	18	10	15	14	15	20	22	13	18	5	271
2	9	14	8	11	7	8	14	18	13	6	7	3	182
4	4	7	3	3	6	7	7	6	3	4	1	-	73
5	1	-	-	2	1	-	1	1	1	1	-	-	12
6	-	-	-	-	-	-	-	-	-	-	-	-	0
7	5	5	2	4	4	4	3	5	2	4	3	1	60

Sources: References 35 and 36

TABLE 31 - SPECIFICATIONS FOR AVIATION GASOLINES (TAKEN FROM REFERENCE 41)

	Grade 80-87	Grade 91-98	Grade 100-130	Grade 108-135	Grade 115-145
Knock value, min, octane number, lean rating	80	91	100	Isooctane plus 0.22 ml of tetraethyllead per gallon	Isooctane plus 0.47 ml of tetraethyllead per gallon
Knock value, min, octane number, rich rating	87	98	Isooctane plus 1.28 ml of tetraethyllead per gallon	Isooctane plus 1.68 ml of tetraethyllead per gallon	Isooctane plus 2.8 ml of tetraethyllead per gallon
Color	Red	Blue	Green	Brown	Purple
Dye content:					
Permissible blue dye, max, mg per gal	0.5	5.7	4.7	3.1	4.7
Permissible yellow dye, max, mg per gal	none	none	7.0	none	none
Permissible red dye, max, mg per gal	8.65	none	none	2.7	3.27
Permissible orange dye, max, mg per gal	none	none	none	6.0	none
Tetraethyllead, max, ml per gal	0.5	2.0	3.0	3.0	4.6
Net heat of combustion, min, Btu per lb	18 720	18 720	18 720	18 800	18 800

TABLE 31 - SPECIFICATIONS FOR AVIATION GASOLINES (TAKEN FROM REFERENCE 41) Continued

Requirements for All Grades	
Distillation temperature, deg F	
10 per cent evaporated, max	158
50 per cent evaporated, max	221
90 per cent evaporated, min	212
90 per cent evaporated, max	257
Final boiling point, max, deg F	338
Sum of 10 and 50 per cent evaporated temperatures, min, deg F (deg C)	307
Distillation recovery, min, per cent	97
Distillation residue, max, per cent	1.5
Distillation loss, max, per cent	1.5
Acidity of distillation residue	Shall not be acid
Vapor pressure, max, lb	7.0
Potential gum (5 hr aging gum), max, mg per 100 ml	6
Visible lead precipitate, max, mg per 100 ml	3
Sulfur, max, per cent	0.05
Freezing point, max, deg F (deg C)	- 72 (-58)
Water tolerance	Volume change not to exceed ± 2 ml
Permissible antioxidants, max, lb per 1000 bbl (42 gal)	4.2

TABLE 32 - PROPERTIES OF AVIATION TURBINE FUELS

Property	Fuel					
	Type A	JP-4	JP-5	JP-6	JP-150	Decalin
Composition						
Hydrocarbon Constituents						
Paraffins, per cent vol	-	-	-	36	92	0
Naphthenes, per cent vol	-	-	-	47	5	98
Olefins, per cent vol	0	0.8	0.9	1	2	0
Aromatics, per cent vol	17	11	13.3	16	1	2
Naphthalenes, per cent vol	-	-	-	0.1	0.1	0.1
Carbon-to-Hydrogen Ratio, mass	-	-	-	6.1	5.35	6.63
Molecular Weight, approximate	164	112	170	146	120	138
Impurities, per cent mass						
Sulphur, total	0.046	0.04	0.039	0.04	0.002	0.003
Sulphur, mercaptans	0.0002	0.0001	0.001	0.0001	0.0001	0.0002
Gum, existent	0.010	0.006	0.010	0.001	0.001	0.001
Gum, potential	0.010	0.014	0.010	0.001	0.001	0.001
Physical Properties						
ASTM Distillation Temps, deg F						
Initial Boiling Point	354	154	368	334	196	361
10 per cent recovery	373	221	389	342	217	364
50 per cent recovery	412	274	419	364	247	366
90 per cent recovery	477	378	465	428	304	369
End point	509	462	501	492	340	384
Vapor pressure at 100 deg F, psia	-	2.6	0.0	0.2	1.8	0.0
Flash point (PM), deg F	117	-	144	126	80	146
Dynamic Viscosity, lbm per ft sec						
At -30 deg F	0.0048	0.0016	0.0055	-	-	-
At 0 deg F	-	-	-	0.0017	0.0006	0.0048
At 100 deg F	-	-	-	0.00063	0.0003	0.0013
Specific Gravity at 60 deg F	0.8105	0.756	0.813	0.7972	0.7154	0.8888
Freezing Point, deg F	-52	-78	-62	-76	-76	-76
Specific Heat, Btu per lbm deg F						
At 100 deg F	-	-	-	0.48	0.51	0.46
Combustion Properties						
Lower Calorific value						
Btu per lbm	18,569	18,752	18,564	18,594	19,040	18,282
Btu per cu ft	938,000	885,000	942,000	923,000	849,000	1,012,000
Stoichiometric Air-Fuel Ratio	-	-	-	14.7	15.1	14.4
Smoke Point, mm	22	31	25	25	50	24
Luminometer Number	49	78	51	47	138	47
Other Specification Indices						
Bromine Number	-	-	-	1.3	0.02	0.1
Aniline Point, deg F	140.5	133	145.6	137	158	95
Copper Strip Test at 212 deg F	1	1	1A	1A	2A	1

Sources: References 43 and 44

TABLE 33 - SPECIFICATIONS FOR AVIATION TURBINE FUELS

Property	Jet A	Jet A-1	Jet B
Gravity, max, deg API (min, sp gr)	51 (0.7753)	51 (0.7753)	57 (0.7507
Gravity, min, deg API (max, sp gr)	39 (0.8299)	39 (0.8299)	45 (0.8017)
Distillation temperature, deg, F (deg C)			
10 per cent evaporated, max	400 (204.4)	400 (204.4)	-
20 per cent evaporated, max	-	-	290 (143.3)
50 per cent evaporated, max	450 (232.2)	450 (232.2)	370 (187.8)
90 per cent evaporated, max	-	-	470 (243.3)
Final boiling point, max, deg F (deg C)	550 (287.8)	550 (287.8)	-
Distillation residue, max, per cent	1.5	1.5	1.5
Distillation loss, max, per cent	1.5	1.5	1.5
Vapor pressure, max, lb	-	-	3
Flash point, min, deg F (deg C)	110 (43.3)	110 (43.3)	-
Flash point, max, deg F (deg C)	150 (65.6)	150 (65.6)	-
Freezing point, max, deg F (deg C)	-30 (-38)	-54 (-48)	-56 (-40)
Viscosity at -30 F (-34.4 C), max, cs	15	15	-
Net heat of combustion, min, Btu per lb	18 400	18 400	18 400
Total acidity, max, mg KOH per gram	0.1	0.1	-
Sulfur, max, per cent	0.3	0.3	0.3
Mercaptan sulfur, max, per cent	0.003	0.003	0.003
Water tolerance, vol change, not to exceed, ml	±1	±1	±1
Existent gum, max, mg per 100 ml	7	7	7
Total potential residue, 16 hr, max, mg per 100 ml	14	14	14
Thermal stability at 300 to 400 F (148.9 to 204.4 C):			
Filter press drop, max, in of Hg	12	12	12
Preheater deposit less than	Code 3	Code 3	Code 3
Combustion properties. One of the following requirements shall be met:			
(1) Luminometer number, min	45	45	50
or (2) Smoke point, min	25	25	-
or (3) Smoke point, min	20	20	-
Burning test, 16 hr			

TABLE 33 - SPECIFICATIONS FOR AVIATION TURBINE FUELS (CONTINUED)

Property	Jet A	Jet A-1	Jet B
or (4) Smoke point, min	20	20	-
Naphthalenes, max, per cent	3	3	-
or (5) Smoke volatility index, min	-	-	54
Aromatics, vol, max, per cent	20	20	20
Olefins, vol, max, per cent	-	-	5

Source: Reference 49

TABLE 34 - UNITED STATES CONSUMPTION OF AIRCRAFT FUELS, PAST AND FUTURE

Fiscal Year	Annual Consumption (Millions of Gallons)					
	Piston - Engine Fuels			Turbine - Engine Fuels		
	Air Carrier	General Aviation	Military	Air Carrier	General Aviation	Military
1963	635	245	1,230	2,250	25	4,790
1964	615	255	1,040	2,561	36	4,520
1965	557	277	1,030	3,058	61	5,050
1966	464	333	950	3,907	109	5,540
1967	335	371	850	4,568	129	6,600
1968*	190	415	-	5,560	150	-
1969*	100	440	-	6,840	175	-
1970*	70	470	-	7,470	195	-
1971*	60	500	-	8,010	210	-
1972*	60	530	-	8,620	225	-
1973*	50	560	-	9,500	240	-
1974*	40	590	-	10,350	265	-
1979*	30	780	-	16,450	440	-

*Estimates

Sources: References 15 and 54

TABLE 35 - FUEL CONSUMPTION RATES FOR REPRESENTATIVE ENGINES

Aircraft Class	Representative Engine	Fuel Rates (lbs per hour per engine)					
		Taxi	Idle	Landing	Take-Off	Approach	Climb-Out
1	Pratt & Whitney JT3D	1084	1084	5467	9510	4970	7608
2	Pratt & Whitney JT8D	920	920	3218	7765	2925	6212
3	Pratt & Whitney JT12	540	540	1940	3350	1765	2680
4	Allison 501-D13	594	516	981	2036	892	1629
5	Pratt & Whitney R-2800	360	162	528	2100	480	1680
6	Continental 10-520-A	28	25	28	140	42	112
7	General Electric CT58	370	180	590	880	540	700

Data obtained from engine and aircraft manufacturers.
Fuel rates estimated where manufacturers' data not available.

TABLE 36 - FUEL CONSUMPTION DURING LANDING AND TAKE-OFF OPERATIONS FOR REPRESENTATIVE ENGINES

Aircraft Class	Representative Engine	Fuel Consumed (lbs per Engine)						
		Taxi	Idle	Landing	Take-Off	Approach	Climb-Out	Total LTO-Cycle
1	Pratt & Whitney JT3D	217.4	18.1	36.4	158.5	298.2	279.0	1007.6
2	Pratt & Whitney JT8D	184.0	15.3	16.1	103.5	141.3	196.7	656.9
3	Pratt & Whitney JT12	108.0	9.0	12.9	22.3	47.1	22.3	221.7
4	Allison 501-D13	118.8	8.5	4.9	20.4	66.9	97.8	317.4
5	Pratt & Whitney R-2800	72.0	2.7	5.3	21.0	36.8	140.0	277.8
6	Continental 10-520-A	5.6	0.4	0.1	0.9	2.7	4.7	14.4
7	General Electric CT58	37.0	3.0	0.0	0.0	59.4	77.0	176.4

Table 37- AIRCRAFT FUEL CONSUMPTION DURING AIR TERMINAL OPERATIONS

Air terminal	Estimated average daily consumption in 1967, 1000 lbs		
	Aviation gasoline	Turbine fuels	All fuels
John F. Kennedy International	13	1,472	1,485
Teterboro (General Aviation)	8	0	8
All FAA-controlled and military terminals in New York IAQCR[a]	89	2,336	2,425
Washington National	60	373	433
All FAA-controlled and military terminals in national capital IAQCR[a]	116	992	1,108
Los Angeles International	17	1,453	1,470
Long Beach (General Aviation)	17	31	48
All terminals in Los Angeles County	111	1,637	1,748
All FAA-controlled terminals in United States	4,108	24,340	28,448

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[a] IAQCR = interstate air quality control region

TABLE 38 - COMPOSITION OF EXHAUST PRODUCTS FROM TYPICAL AIRCRAFT ENGINES

Exhaust Species	Concentration Units	Exhaust Composition			
		Radial-Piston Engine		Turbofan Engine	
		Idle	Take-Off	Idle	Take-Off
N_2	Vol. per cent	70.9	65.9	78.5*	78.0*
O_2	"	0.8	0.8	18.4*	16.3*
H_2O	"	11.4*	8.4*	1.5*	2.8*
H_2	"	2.5	7.7	**	**
CO_2	"	8.3	4.6	1.52	2.84
CO	"	5.5	11.6	0.0390	0.0018
Organics (As CH_4)	"	0.6	1.0	0.0132	0.0015
NO_x	Vol. ppm	**	**	12.1	27.9
SO_2	"	**	**	1.0	0.4
Particulates	mg/m^3	**	**	5.5	43.8

Sources: References 55 and 68

* Estimated values

** Values not reported, assumed to be small or negligible

TABLE 39 - DETAILED ANALYSIS OF ORGANIC EMISSIONS FROM A TURBOJET ENGINE

Exhaust Species	Concentration Units	Exhaust Composition		
		Idle	Approach	Take - Off
Total Organics	ppm by vol. as CO_2	224.0	144.0	71.0
Formaldehyde	ppm by vol.	29.0	6.0	60.0
Acetaldehyde	"	1.5	1.5	< 0.6
Propionaldehyde	"	3.0	3.0	< 0.6
Butanaldehyde	"	< 0.6	< 0.6	< 0.6
Pentanaldehyde	"	< 0.6	< 0.6	< 0.6
Ethylene	"	30.0	21.5	< 0.15
Propylene	"	10.0	7.0	< 0.3
Acetylene	"	8.5	6.0	< 0.3
Methane	"	26.0	20.0	3.0
Ethane	"	2.0	1.5	1.5
Propane	"	0.3	< 0.3	< 0.15
Butane	"	< 0.3	< 0.3	< 0.3
Hydrocarbons above C_5	ppm by vol. as CO_2	37.0	28.0	2.0
Other Species				
CO	ppm by vol.	750	590	50
NO_x	"	12	21	210
CO_2	% by vol.	1.095	1.190	2.090
Particulates	mg/m^3	0.5	0.5	27.0

Source: Reference 56

TABLE 40 - EMISSION INDICES FOR AIRCRAFT ENGINES

Aircraft Class	Operating Mode	A/F	Emission index (lb/1000 lb fuel)				
			CO	Organics	NO_x	Particulates	SO_2
1	Idle & Taxi	133	174	75	2.0	0.3	1.0
	Approach	103	8.7	16	2.7	1.1	1.0
	Land Take-Off Climb-Out	75	0.7	0.1	4.3	0.6	1.0
2	Idle & Taxi	132	50	9.6	2.0	0.6	1.0
	Approach	108	6.6	1.4	2.7	2.7	1.0
	Land Take-Off Climb-Out	69	1.2	0.6	4.3	2.5	1.0
3	Idle & Taxi	127	118	11.5	2.0	0.1	1.0
	Approach	91	11	0.6	2.7	0.4	1.0
	Land Take-Off Climb-Out	58	4	0.3	4.3	0.3	1.0
4	Idle & Taxi	106	24.8	8.1	3.7	0.6	1.0
	Approach	133	1.6	0	2.9	1.0	1.0
	Land Take-Off Climb-Out	57	2.3	3.2	3.1	0.8	1.0

TABLE 40 - EMISSION INDICES FOR AIRCRAFT ENGINES (CONTINUED)

Aircraft Class	Operating Mode	A/F	Emission index (lb/1000 lb fuel)				
			CO	Organics	NO_x	Particulates	SO_2
5	Idle	10.0	600	160	0	2	0.2
	Taxi	11.5	900	90	3	2	0.2
	Approach	12.0	800	60	5	2	0.2
	Land Take-Off Climb-Out	9.5	1250	190	0	2	0.2
6	Idle	10.0	600	160	0	2	0.2
	Taxi	11.5	900	90	3	2	0.2
	Approach	12.0	800	60	5	2	0.2
	Land Take-Off Climb-Out	11.0	1050	110	1	2	0.2
7	Idle & Taxi	111	118	11.5	2.0	1.0	1.0
	Approach	75	11	0.6	2.7	1.5	1.0
	Climb-Out	63	4	0.3	4.3	1.5	1.0

TABLE 41a - TURBINE ENGINE EMISSION DATA
IDLE CONDITION

Engine	Fuel	F/A	Fuel Flow lb/hr	Emission Index (lb per lb fuel X1000)			
				CO	Organics (as CH_4)	NO_x (as NO)	Particulates
Turbojets							
A	-	0.0064	1120	63.0	4.2*	1.5	12.5*
B	-	0.0061	-	58.5	26.3	2.2	-
C	JP4	0.0052	890	24.3	16.2	2.6	-
D	JP4	0.0065	1140	90.2	69.6	0.4	0.3
E	JP5	0.0065	1220	98.3	62.4	0.4	0.1
F	JP4	0.0061	1697	76.2	41.6	0.7	0.3
G	JP5	0.0065	1678	166.8	82.2	0.6	0.7
H	JP4	0.0079	542	117.5	11.5	0.5	0.1
I	JP5	0.0086	568	103.6	12.1	0.4	0.1
J	Kerosine	0.0099	1140	-	11.4	0.5	1.1
K	Kerosine	0.0125	600	-	-	-	0.4
Turbofans							
L	Kerosine	0.0089	-	33.3	12.8	2.4	-
M	JP4	0.0065	1000	29.2	60.0	1.8	2.4
N	JP4	0.0075	1087	174.4	75.1	0.2	0.3
O	JP5	0.0087	1212	124.7	56.0	0.1	0.4
P	JP4	0.0076	918	49.9	9.6	1.5	0.6
Q	JP5	0.0092	850	67.4	9.2	0.4	0.8
R	Kerosine	-	-	-	-	-	1.0
S	Kerosine	0.011	936	128.2	19.1	2.2	0.1
T	JP4	-	-	30.0	5.0	0.7	< 0.5
Turboprops							
U	JP4	0.008	675	13.3	7.0	1.6	-
V	Kerosine	0.009	180	-	-	-	1.0
W	JetAl	0.0094	516	24.8	8.1	3.7	0.6
X	JetAl	0.0094	514	-	-	-	0.7
Y	Kerosine	0.0078	741	31.3	1.5	5.9	0.1

*Particulate emissions reported include organic materials condensed during sample collection.

TABLE 41b - TURBINE ENGINE EMISSION DATA
APPROACH MODE

Engine	Fuel	F/A	Fuel Flow lb/hr	Emission Index (lb per lb fuel X1000)			
				CO	Organics (as CH_4)	NO_x (as NO)	Particulates
Turbojets							
A	-	0.0084	3820	8.0	<3.5*	3.9	7.5*
B	-	-	-	-	-	-	-
C	JP4	-	-	-	-	-	-
D	JP4	0.0092	3807	8.7	3.2	1.3	0.9
E	JP5	0.0092	3864	11.4	11.0	1.7	1.0
F	JP4	0.0084	4784	8.7	3.5	1.5	0.6
G	JP5	0.0089	4565	12.3	8.6	1.9	1.3
H	JP4	0.0110	1766	11.5	0.6	1.7	0.4
I	JP5	0.0110	1768	10.8	0.8	1.5	0.5
J	Kerosine	-	-	-	-	-	-
K	Kerosine	0.0128	-	-	-	-	0.5
Turbofans							
L	Kerosine	-	-	-	-	-	-
M	JP4	0.0119	5290	2.5	1.9	1.3	2.0
N	JP4	0.0097	4970	8.7	15.9	1.9	1.1
O	JP5	0.0102	5080	7.1	9.8	1.9	1.6
P	JP4	0.0093	2824	6.6	1.4	2.2	2.7
Q	JP5	0.0114	3370	5.0	0.6	1.8	2.8
R	Kerosine	-	-	-	-	-	-
S	Kerosine	0.011	3350	11.0	0.0	1.9	1.1
T	JP4	-	-	-	-	-	-
Turboprops							
U	JP4	0.0143	1515	2.7	0.1	2.0	-
V	Kerosine	0.0133	540	-	-	-	1.5
W	JetAl	0.0075	892	1.6	0.0	2.9	1.0
X	JetAl	0.0145	1718	-	-	-	0.6
Y	Kerosine	0.009	780	34.8	2.5	7.0	0.0

*Particulate emissions reported include organic materials condensed during sample collection.

TABLE 41c - TURBINE ENGINE EMISSION DATA
TAKE - OFF MODE

				Emission Index (lb per lb fuel X1000)			
Engine	Fuel	F/A	Fuel Flow lb/hr	CO	Organics (as CH_4)	NO_x (as NO)	Particulates
Turbojets							
A	-	0.017	13000	6.5	< 1.5*	1.3	13.5*
B	-	0.0143	-	0.8	1.2	5.3	-
C	JP4	0.0143	8300	2.2	0.2	4.3	-
D	JP4	0.0164	10174	1.0	0.1	2.4	0.6
E	JP5	0.0166	11387	0.9	0.4	2.8	0.8
F	JP4	0.0158	14102	0.6	0.5	0.8	0.6
G	JP5	0.0161	13953	1.1	0.1	0.8	1.5
H	JP4	0.0172	3334	3.9	0.3	1.1	0.3
I	JP5	0.0174	3353	3.8	0.3	1.0	0.4
J	Kerosine	0.0144	8310	-	0.0	5.3	1.8
K	Kerosine	0.0183	2900	-	-	-	0.4
Turbofans							
L	Kerosine	0.0164	-	2.4	2.9	5.0	-
M	JP4	0.0133	8550	0.5	0.3	2.1	1.9
N	JP4	0.0133	9510	<0.7	0.1	1.2	0.6
O	JP5	0.0135	9400	0.7	0.3	1.0	0.9
P	JP4	0.0145	7766	1.2	0.6	1.9	2.5
Q	JP5	0.0181	10050	1.1	0.2	3.0	2.2
R	Kerosine	0.0149	9035	-	-	-	2.0
S	Kerosine	0.0202	7745	4.8	0.6	21.8	2.1
T	JP4	-	-	<1.0	0.1	2.0	1.0
Turboprops							
U	JP4	0.0184	1970	1.8	0.2	2.5	-
V	Kerosine	0.0158	730	-	-	-	1.5
W	JetAl	0.0175	2035	2.3	3.2	3.1	0.8
X	JetAl	0.0201	2349	-	-	-	0.4
Y	Kerosine	-	-	-	-	-	-

*Water injection used. Particulate emissions reported include organic materials condensed during sample collection.

TABLE 42 - ENGINE EMISSION LEVELS DURING A LANDING AND TAKE - OFF CYCLE

Aircraft class	Mode*	Pollutant Specie total flow in lbs per engine			
		CO	HC	NO_x	Particulate
1	1	37.83	16.30	0.43	0.07
	2	3.15	1.36	0.04	0.01
	3	0.14	0.02	0.84	0.12
	4	2.79	4.80	2.00	0.50
	Total	43.91	22.48	3.31	0.69
2	1	9.20	1.77	0.37	0.11
	2	0.77	0.15	0.03	0.01
	3	0.14	0.07	0.51	0.30
	4	1.17	0.32	1.23	0.87
	Total	11.28	2.31	2.14	1.29
3	1	12.74	1.24	0.22	0.01
	2	1.06	0.10	0.02	0.0
	3	0.14	0.01	0.15	0.01
	4	0.61	0.03	0.22	0.03
	Total	14.55	1.38	0.61	0.05
4	1	2.95	0.96	0.44	0.07
	2	0.21	0.07	0.03	0.01
	3	0.06	0.08	0.08	0.02
	4	0.33	0.31	0.50	0.15
	Total	3.55	1.42	1.05	0.25
5	1	64.80	6.48	0.22	0.14
	2	1.62	0.43	0.0	0.01
	3	32.88	5.00	0.0	0.05
	4	204.44	28.81	0.18	0.35
	Total	303.70	40.72	0.40	0.56
6	1	5.04	0.50	0.02	0.01
	2	0.24	0.06	0.0	0.01
	3	1.04	0.11	0.0	0.0
	4	7.10	0.68	0.02	0.02
	Total	13.42	1.35	0.04	0.04
7	1	4.37	0.43	0.07	0.04
	2	0.35	0.03	0.01	0.04
	3	----	----	----	----
	4	0.96	0.06	0.49	0.21
	Total	5.68	0.52	0.57	0.29

Source: Reference 4

***1 - taxi, 2 - idle, 3 - landing and take - off, 4 - approach and climb-out**

TABLE 43 - RELATIVE EMISSION LOADS BY ENGINE AND AIRCRAFT TYPE

Class	CO	HC	NO_x	Part.
1	1.0	1.0	1.0	1.0
2	0.27	0.10	0.65	1.87
3	0.35	0.06	0.18	0.07
4	0.09	0.06	0.32	0.36
5	7.29	1.81	0.12	0.81
6	0.32	0.06	0.01	0.06
7	0.14	0.02	0.17	0.42

(a) By Engine Type

Class	Aircraft	E	CO	HC	NO_x	Part.
1	707	4	1.0	1.0	1.0	1.0
2	727	3	0.20	0.08	0.49	1.40
3	Sabreliner	2	0.17	0.03	0.09	0.04
4	Electra	4	0.09	0.06	0.32	0.36
5	DC6	4	7.29	1.81	0.12	0.81
6	Cessna 210	1	0.08	0.015	0.003	0.015
7	Helicopter V107	2	0.07	0.01	0.085	0.21

(b) By Aircraft Type

TABLE 44 - AIRCRAFT EXHAUST EMISSIONS AT NEW YORK AREA TERMINALS - 1967

Terminal	Aircraft Type	Operating Mode	Average Emissions (lb/day)			
			CO	Organics	NO_x	Particulates
J. F. Kennedy International	Turbine (Classes) 1,2,3,4,7)	Taxi	44,900	17,900	730	150
		Idle	3,700	1,500	60	20
		Land, Take-Off	200	100	1,160	290
		Approach, Climb-Out	3,700	5,100	2,870	1,040
		Total Cycle	52,500	24,600	4,820	1,500
	Piston (Classes 6 & 7)	Taxi	3,300	300	10	10
		Idle	100	-	-	-
		Land, Take-Off	1,500	200	-	-
		Approach, Climb-Out	9,200	1,300	10	20
		Total Cycle	14,100	1,800	20	30
	All Types	Total Cycle	66,700	26,400	4,840	1,530
Teterboro (New Jersey)	Turbine (Classes 1,2,3,4,7)	Taxi	(Turbine - engine aircraft activity assumed to be negligible.)			
		Idle				
		Land, Take-Off				
		Approach, Climb-Out				
		Total Cycle				
	Piston (Classes 6 & 7)	Taxi	2,800	300	10	10
		Idle	100	-	-	-
		Land, Take-Off	600	-	-	-
		Approach, Climb-Out	3,900	400	10	10
		Total Cycle	7,400	700	20	20
	All Types	Total Cycle	7,400	700	20	20
All Major New York Area Terminals	Turbine (Classes 1,2,3,4,7)	Taxi	63,400	23,100	1,310	280
		Idle	5,300	1,900	110	40
		Land, Take-Off	400	200	1,760	540
		Approach, Climb-Out	5,400	6,400	4,450	1,860
		Total Cycle	74,500	31,600	7,630	2,720
	Piston (Classes 6 & 7)	Taxi	24.500	2,400	90	50
		Idle	900	200	-	30
		Land, Take-Off	9,000	1,300	-	10
		Approach, Climb-Out	57,200	7,300	80	110
		Total Cycle	91,600	11,200	170	200
	All Types	Total Cycle	166,100	42,800	7,800	2,920

TABLE 45 - AIRCRAFT EXHAUST EMISSIONS AT WASHINGTON AREA TERMINALS - 1967

Terminal	Aircraft Type	Operating Mode	Average Emissions (lb/day)			
			CO	Organics	NO_x	Particulates
Washington National	Turbine (Classes 1,2,3,4,7)	Taxi	5,000	1,200	320	70
		Idle	400	100	20	10
		Land, Take-Off	100	100	220	110
		Approach, Climb-Out	600	300	660	370
		Total Cycle	6,100	1,700	1,220	560
	Piston (Classes 6 & 7)	Taxi	14.200	1,400	50	30
		Idle	400	100	-	-
		Land, Take-Off	7,000	1,000	-	10
		Approach, Climb-Out	43,400	6,100	40	80
		Total Cycle	65,000	8,600	90	120
	All Types	Total Cycle	71,100	10,300	1,310	680
All Major Washington Area Terminals	Turbine (Classes 1,2,3,4,7)	Taxi	31,800	5,800	860	120
		Idle	2,600	400	70	30
		Land, Take-Off	400	100	630	200
		Approach, Climb-Out	2,100	1,100	1,510	620
		Total Cycle	36,900	7,400	3,070	970
	Piston (Classes 6 & 7)	Taxi	27,900	2,800	100	60
		Idle	800	200	-	10
		Land, Take-Off	13,300	2,000	-	20
		Approach, Climb-Out	83,300	11,600	80	150
		Total Cycle	125,300	16,600	180	240
	All Types	Total Cycle	162,200	24,000	3,250	1,210

TABLE 46 - AIRCRAFT EXHAUST EMISSIONS AT LOS ANGELES AREA TERMINALS - 1967

Terminal	Aircraft Type	Operating Mode	Average Emissions (lb/day)			
			CO	Organics	NO_x	Particulates
Los Angeles International	Turbine (Classes 1,2,3,4,7)	Taxi	46,000	18,400	710	140
		Idle	3,900	1,500	60	20
		Land, Take-Off	300	100	1,150	270
		Approach, Climb-Out	3,700	5,300	2,840	990
		Total Cycle	53,900	25,300	4,760	1,420
	Piston (Classes 6 & 7)	Taxi	4,400	400	20	20
		Idle	100	-	-	-
		Land, Take-Off	1,900	300	-	-
		Approach, Climb-Out	12,300	1,700	10	20
		Total Cycle	18,700	2,400	30	40
	All Types	Total Cycle	72,600	27,700	4,790	1,460
Long Beach	Turbine (Classes 1,2,3,4,7)	Taxi	1,500	200	30	-
		Idle	100	-	-	-
		Land, Take-Off	-	-	20	-
		Approach, Climb-Out	100	-	40	10
		Total Cycle	1,700	200	90	10
	Piston (Classes 6 & 7)	Taxi	5,600	500	20	20
		Idle	300	100	-	10
		Land, Take-Off	1,400	200	-	-
		Approach, Climb-Out	9,300	1,000	20	20
		Total Cycle	16,600	1,800	40	50
	All Types	Total Cycle	18,300	2,000	130	60
All Los Angeles County Terminals	Turbine (Classes 1,2,3,4,7)	Taxi	53,200	19,700	870	160
		Idle	4,400	1,600	70	20
		Land, Take-Off	300	100	1,280	300
		Approach, Climb-Out	4,200	5,600	3,130	1,100
		Total Cycle	62,100	27,000	5,360	1,580
	Piston (Classes 6 & 7)	Taxi	36,100	3,600	140	70
		Idle	1,600	400	-	60
		Land, Take-Off	9,200	1,100	-	10
		Approach, Climb-Out	61,000	6,700	140	150
		Total Cycle	107,900	11,800	280	290
	All Types	Total Cycle	170,000	38,800	5,640	1,870

TABLE 47 - AIRCRAFT EXHAUST EMISSIONS AT ALL FAA - CONTROLLED TERMINALS - 1967

Aircraft Class	Operational Mode	Average Emissions (1000 lb/day)			
		CO	Organics	NO_x	Particulates
1	Taxi	370	160	4.2	0.7
	Idle	31	13	0.4	0.1
	Land, Take-Off	1	-	8.2	1.1
	Approach, Climb-Out	27	47	19.6	4.9
	Total Cycle	429	220	32.4	6.8
2	Taxi	105	20	4.2	1.3
	Idle	9	2	0.4	0.1
	Land, Take-Off	1	1	5.8	3.4
	Approach, Climb-Out	13	3	14.0	9.9
	Total Cycle	128	26	24.4	14.7
3	Taxi	176	17	3.0	0.2
	Idle	15	2	0.3	-
	Land, Take-Off	2	-	2.1	0.1
	Approach, Climb-Out	8	-	3.0	0.4
	Total Cycle	201	19	8.4	0.7
4	Taxi	35	11	5.2	0.8
	Idle	2	1	0.3	0.1
	Land, Take-Off	1	1	0.9	0.2
	Approach, Climb-Out	4	4	5.9	1.8
	Total Cycle	42	17	12.3	2.9
5	Taxi	713	71	2.4	1.5
	Idle	18	5	-	0.1
	Land, Take-Off	362	55	-	0.6
	Approach, Climb-Out	2250	317	2.0	3.9
	Total Cycle	3343	448	4.4	6.1
6	Taxi	368	36	1.5	0.7
	Idle	17	4	-	0.7
	Land, Take-Off	76	8	-	-
	Approach, Climb-Out	518	50	1.4	1.5
	Total Cycle	979	98	2.9	2.9
7	Taxi	5	1	0.1	0.1
	Idle	1	-	-	-
	Land, Take-Off	-	-	-	-
	Approach, Climb-Out	1	-	0.6	0.3
	Total Cycle	7	1	0.7	0.4
All Classes	Total Cycle	5129	829	85.5	34.5

TABLE 48 - POLLUTANT EMISSION BY AIRCRAFT DURING AIR TERMINAL OPERATIONS - 1967

		Estimated Average Daily Emissions (1000 lb/day)			
Air Terminal	Operations[b]	CO	Organics	NO_x	Particulates
J. F. Kennedy International	Ground	54	20	1.9	0.4
	Flight	13	6	2.9	1.1
	Total	67	26	4.8	1.5
Teterboro (General Aviation)	Ground	3	0.3	0.01	0.01
	Flight	4	0.4	0.01	0.01
	Total	7	0.7	0.02	0.02
All FAA - controlled and military terminals in New York IAQCR[a]	Ground	103	30	3.2	0.9
	Flight	63	13	4.6	2.0
	Total	166	43	7.8	2.9
Washington National	Ground	27	4	0.6	0.2
	Flight	44	6	0.7	0.5
	Total	71	10	1.3	0.7
All FAA - controlled and military terminals in national capital IAQCR[a]	Ground	77	11	1.6	0.4
	Flight	85	13	1.6	0.8
	Total	162	24	3.2	1.2
Los Angeles International	Ground	57	21	1.9	0.5
	Flight	16	7	2.9	1.0
	Total	73	28	4.8	1.5
Long Beach (General Aviation)	Ground	9	1	0.07	0.03
	Flight	9	1	0.06	0.03
	Total	18	2	0.13	0.06
All terminals in Los Angeles County	Ground	105	27	2.3	0.7
	Flight	65	12	3.3	1.2
	Total	170	39	5.6	1.9
All FAA - controlled terminals in the United States	Ground	2316	408	39.0	11.8
	Flight	2813	421	46.5	22.7
	Total	5129	829	85.5	34.5

[a] IAQCR = interstate air quality control region

[b] Ground Operations = taxi, idle, take-off and landing runs
Flight Operations = approach and climb-out

TABLE 49 - AIRCRAFT EXHAUST EMISSIONS DURING CRUISE

Emission Indices at Cruise (lb/1000 lb fuel):

Engine Type	CO	Organics	NO_x	Particulates
Piston (A/F = 15)	100	15	50	2
Turbine	1	0.5	4	1

Fuel Consumption - 1967 (10^6 lb):

Fuel Type	Air Carrier	General Aviation	Military
Av. Gasoline	1,980	2,190	5,400
Turbine Fuels	27,000	760	26,600

Total Emissions - 1967 (10^6 lb)*:

	CO	Organics	NO_x	Particulates
Air Carrier	180	34	166	25
General Av.	176	26	90	4
Military	454	75	300	30
Total	810	135	556	59

*80 per cent of all fuel assumed to be consumed during cruise.

TABLE 50 - TOTAL EMISSIONS IN THE UNITED STATES FROM AIRCRAFT (1967)

Operations	Emissions - 1967 (10^6 lb)			
	CO	Organics	NO_x	Particulates
At FAA - Controlled Terminals	1860	302	31	12
At Military Terminals	2079	257	38	7
Cruise	810	135	556	59
Total	4749	694	625	78

TABLE 51 - ELEMENTS USED AND ASSUMPTIONS MADE IN CALCULATION OF EMISSION LOADS

Elements Used	Assumptions Made
1. Aircraft Activity by Aircraft Type	a. Air carrier activity, other than certificated route air carriers, consists entirely of class 1 and class 2 aircraft.
	b. General aviation activity consists entirely of class 6 aircraft with average power of 400hp.
	c. Military activity at urban air terminals consists of aircraft classes 3(50%), 4(15%), 5(10%), 6(20%) and 7(5%).
2. Aircraft Operations	a. All aircraft within a given class follow the same operational cycle during air terminal operations as defined in Table 2.
3. Engine Fuel Consumption Rates	a. Wherever fuel consumption rates were not reported by engine manufacturers for specific operational modes, the following relationships were used: Taxi rate = Idle rate Climb-out rate = 0.8 Take-off rate Landing rate = 1.1 Approach rate
4. Pollutant Emission Rates	a. Emission indices for CO, organics and NO_x for aircraft piston engines are equal to emission indices for automobile engines. (Assumed to vary similarly with A-F ratio.
	b. Emission index for particulates from aircraft piston engines assumed equal to 2.0 lb/1000 lb fuel.
	c. Emission indices and emission rates for all civil aircraft engines within a given aircraft class are equal to those of the representative engine for that class.

TABLE 51 - ELEMENTS USED AND ASSUMPTIONS MADE IN CALCULATION OF EMISSION LOADS (CONTINUED)

Elements Used	Assumptions Made
	d. Emission rates for military class 3 aircraft are six times as great as the rates of emission from the representative class 3 engine. e. For turbine-engine aircraft, emission rates in the taxi mode are equal to those at idle.

TABLE 52 - ERROR FACTORS FOR AIRCRAFT EMISSION LOADS

Aircraft Class	Idle Time (Minutes)	Error Factor for Total LTO - Cycle (Maximum Load/Average Load)*			
		CO	Organics	NO_x	Particulates
1	10	3.3	3.1	2.2	2.3
	30	6.4	5.5	2.7	2.8
2	10	3.2	3.2	2.3	2.1
	30	6.0	5.8	2.8	2.4
3	10	3.3	2.6	2.6	2.0
	30	6.2	6.2	3.9	2.0
4	10	3.1	2.9	2.5	2.7
	30	5.4	4.9	3.7	4.3
5	10	2.1	2.2	2.0	2.3
	30	2.3	2.6	2.0	3.0
6	10	2.3	2.8	2.0	6.5
	30	3.0	4.6	2.0	16.5
7	10	3.1	3.0	2.3	4.5
	30	5.6	5.3	3.0	10.0

* Average load is the value of the total load per engine per LTO - cycle used in this analysis and listed in Table 42. Maximum load is based upon increased idle time from one minute to value shown, and emission indices increased by 100 per cent over those listed in Table 40.

TABLE 53 - AIRCRAFT ACTIVITY DURING BUSY AND PEAK HOURS

Air Terminal	Activity Ratios	
	Busy Hour / Avg. Hour (1)	Peak Hour / Avg. Hour
J. F. Kennedy International	1.58	2.91 (2)
Washington National	1.50	3.14 (2)
Los Angeles International	1.48	3.42 (3)
Teterboro		5.61 (3)
Long Beach Municipal		5.78 (3)

(1) Busy hour activity = average hourly rate between 10:00 AM and 10:00 PM

(2) FAA - Proposed rates used

(3) FAA - reported data for FY 1965. (Ref 34)

TABLE 54 - MAXIMUM POSSIBLE EMISSION LOADS AT J. F. KENNEDY AIRPORT DURING 1967

Aircraft Type		Pollutant Specie CO	HC	NO_x	Particulates
Jet	Average Load	2092	1026	201	63
	*Scale-up Factor	17.5	16.2	9.5	8.4
Piston	Average Load	588	76	1	1
	*Scale-up Factor	6.7	7.6	5.8	8.8
	Max Load lbs per hr	40500	17200	1900	542

$$\text{*Scale-up Factor} = \frac{\text{Peak}}{\text{Average}} \text{ Hourly Activity Factor (Table 53)}$$

$$\times \text{ Max Error Factor}$$

The following assumptions are made in calculating the maximum error factor:

Idle Time = 30 minutes

Emission indices equal to twice those given in Table 40.

TABLE 55 - EMISSIONS BY CIVIL AIRCRAFT AT ALL FAA-CONTROLLED TERMINALS - 1967 & 1979

Aircraft Class	Emissions (1000 lb/day) CO 1967	CO 1979	Organics 1967	Organics 1979	NO_x 1967	NO_x 1979	Particulates 1967	Particulates 1979
1	429	1195	220	613	32.4	169.0	6.8	18.9
2	129	356	26	72	24.4	126.2	14.7	40.6
3	0	0	0	0	0	0	0	0
4	35	36	14	14	10.3	10.6	2.4	2.5
5	2795	475	375	64	3.7	0.6	5.1	0.9
6	963	4860	97	565	2.9	11.3	2.9	13.5
7	5	12	0.4	1	0.5	1.2	0.2	0.5
Total	4356	6934	732	1329	74.2	318.9	32.1	76.9
Per Cent Change	+59		+81		+330		+139	

Method Used to Forecast 1979 Emissions:

1979 Emissions = (AR) (ER) (1967 Emissions)

AR = Ratio of 1979 activity (LTO - cycles per year) to 1967 activity by aircraft class.

Aircraft Class	1	2	3	4	5	6	7	Total
AR	3.5	3.4	-	1.0	0.2	3.9	2.5	3.5

ER = Ratio of emission per LTO cycle in 1979 to emission per LTO cycle in 1967 as affected by equipment changes.

ER = ABC + (1-C)
where A = ratio of fuel consumption/LTO cycle, 1979 to 1967
B = ratio of mean emission index, 1979 to 1967
C = fraction of aircraft in class affected by change

TABLE 55 - EMISSIONS BY CIVIL AIRCRAFT AT ALL FAA-CONTROLLED TERMINALS - 1967 & 1979 (CONTINUED)

Assumptions					
Aircraft Class	Pollutant	A	B	C	ER
1 and 2	CO	1.3	0.5	0.5	0.8
	Organics	1.3	0.5	0.5	0.8
	NO_x	1.3	1.5	0.5	1.5
	Particulates	1.3	0.5	0.5	0.8
5	CO	1.2	1.1	1.0	1.3
	Organics	1.2	1.3	1.0	1.5
	NO_x	1.2	0.8	1.0	1.0
	Particulates	1.2	1.0	1.0	1.2

TABLE 56 - LAND USE NEAR J. F. KENNEDY, WASHINGTON NATIONAL, AND LOS ANGELES INTERNATIONAL AIRPORTS

Distance from Airport (miles)	JFK*	DCA	LAX*
0-1	Sparse residential, light residential and commercial	Sparse residential and commercial	Dense residential, commerical; light and heavy industrial
1-2	Dense residential and commercial	Dense residential light commerical, and government offices	Dense residential and commercial; light industrial
2-3	Dense residential and commercial	Dense commercial, government offices and residential	Dense residential and commercial; light industrial

* From Reference 119

TABLE 57 - SOURCE DATA USED WITH THE AIRPORT AREA-SOURCE MODEL

Airport	Emmision Densities ($g/m^2/sec$)				Airport Area* (mi^2)
	CO	Organics	NO_x	Particulates	
J. F. Kennedy International	25	9.2	0.92	0.21	4.5
Washington National	62	8.8	0.95	0.53	0.9
Los Angeles International	39	15.0	1.3	0.32	3.0

*Estimated area used for aircraft operations less than total airport area.

TABLE 58 - COMPARISON OF CONCENTRATIONS OF AIRCRAFT EMISSIONS AT AIR TERMINALS WITH COMMUNITY CONCENTRATIONS

Location	Concentration			
	CO ppm	Organics ppm CH_2	NO_x ppm	Particulates $\mu g/m^3$
J. F. Kennedy Terminal				
Neutral[a]	1.5	1.2	0.04	15
Stable[a]	4.1	3.0	0.09	39
Washington National Terminal				
Neutral	3.0	0.8	0.03	27
Stable	7.9	2.2	0.09	78
Washington, D.C. - 1965 Avg (Ref 73)	3.7	2.1[b]	0.07	NA
Los Angeles International Terminal				
Neutral	2.3	1.8	0.04	21
Stable	6.1	4.8	0.12	56
Los Angeles - 1966 Avg (Ref 116)	10	NA	0.09	NA
Recommended community limit values (Refs 61, 73, 136)	15-30	3-4	0.25	80-120

[a] refers to meteorological conditions

[b] composition unknown

[c] concentrations at air terminals calculated using airport area source model and following assumptions:
(1) receptor 100 meters downwind of airport edge,
(2) wind speed 5 miles per hour.

TABLE 59 - EMISSIONS PER UNIT OF PATH LENGTH

Aircraft Class*	Operating Mode**	Contaminant Emissions (lbs/1000 feet of travel)			
		CO	HC	NO_x	Particulates
1	1	9.6	4.12	.12	.016
	3	.046	.007	.28	.04
	4	.023	.21	.09	.022
5	1	16.4	1.6	.05	.04
	3	23.9	3.7	-	.04
	4	6.5	.92	.01	.01

* Class 1 - large turbine engined aircraft
Class 5 - large piston engined aircraft

** Mode 1 - taxi
Mode 3 - land/take-off
Mode 4 - approach/climb-out

TABLE 60 - DENSITY OF AIRCRAFT EXHAUST EMISSIONS AT AIR TERMINALS COMPARED WITH EMISSIONS IN SURROUNDING REGIONS

	Average Emission Density in 1967[d] 1000 lb/day per sq mi				
Region	Land Area sq mi[c]	CO	Organics	NO_x	Particulates
New York City:					
J. F. Kennedy International Terminal	4.5	12.0	4.4	0.44	0.11
Queens County (Refs 120, 126 & 127)	113	30.2	8.4	5.72	1.10
Kings County (Refs 120, 126 & 127)	76	25.4	7.2	6.00	2.48
National Capital:					
Washington National Terminal	0.9	30.0	4.4	0.67	0.22
Arlington County (Ref 128)	25.8	32.6	5.2	1.86	0.54
Alexandria City (Ref 128)	15.7	24.0	6.0	4.70	1.00
Washington, D. C. (Ref 128)	61.4	32.0	8.0	3.80	1.20
Los Angeles[a]:					
Los Angeles International Terminal	3.0	18.7	7.3	0.67	0.17
Los Angeles County (Ref 117)	4,083	5.0	1.3	0.39	0.05
Los Angeles Basin[b] (Ref 117)	1,250	16.2	4.3	1.29	0.16

[a] rule 62 period (summer months)

[b] 90 per cent of Los Angeles County emissions assumed to occur in Los Angeles Basin

[c] estimated area used for aircraft operations; less than total airport area

[d] based upon emissions during ground operations only

TABLE 61 - VARIATIONS IN EMISSION DENSITIES IN URBAN AREAS

Region	Emission Density (tons/day per mi^2)					
	CO			Particulate		
	max val	avg near airport	min val	max val	avg near airport	min val
New York City:						
Queens County	42.5	16	0.8	14	.21	0.16
Kings County	69	30	1.2	27	1.5	.07
National Capital:						
Arlington County	29	28	4.2	0.6	0.6	0.1
Alexandria City	37	37	7.6	0.5	0.5	0.3
Washington, D.C.	107	-	5	2.1	-	0.1

TABLE 62 - AIRCRAFT ENGINE EMISSIONS COMPARED WITH EMISSIONS FROM OTHER SOURCES (1967 AVERAGE DAILY EMISSIONS)

	CO		Organics		NO$_x$		Particulates	
	1,000 lb/day	% of Total	1,000 lb/day	% of Total	1,000 lb/day	% of Total	1,000 lb/day	% of Total
New York IAQCR[a]								
Aircraft operations	166	0.6	43		7.8		2.9	0.2
Ground - JFK	54		20		2.0		0.5	
Ground - All terminals	103		30		3.2		0.9	
Flight	63		13		4.6		2.0	
Surface transportation	27,800	95.0					189	15.0
Stationary sources	1,290	4.4					1,070	84.8
All sources	29,300	100.0					1,260	100.0
National capital IAQCR[a]								
Aircraft operations	162	2.3	24	1.4	3.2	0.4	1.2	0.6
Ground - Washington National	27		4		0.6		0.2	
Ground - all terminals	77		11		1.6		0.4	
Flight	85		13		1.6		0.8	
Surface transportation	6,800	96.5	1,510	88.3	285	38.6	32	16.9
Stationary sources	88	1.2	176	10.3	450	61.0	156	82.5
All sources	7,050	100.0	1,710	100.0	738	100.0	189	100.0
Los Angeles County								
Aircraft operations	170	0.8	39	0.7	5.6	0.3	1.9	1.0
Ground - LAX	56		22		1.9		0.5	
Ground - All terminals	105		27		2.4		0.7	
Flight	65		12		3.2		1.2	
Surface transportation	19,950	98.3	3,740	69.5	1,800	67.3	92	47.5
Stationary sources[b]	190	0.9	1,600	29.8	520	32.4	100	51.5
All sources	20,310	100.0	5,380	100.0	1,610	100.0	194	100.0

Sources: References 117, 120, 126, 127 & 128.

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[a] interstate air quality control region

[b] rule 62 period (summer months)

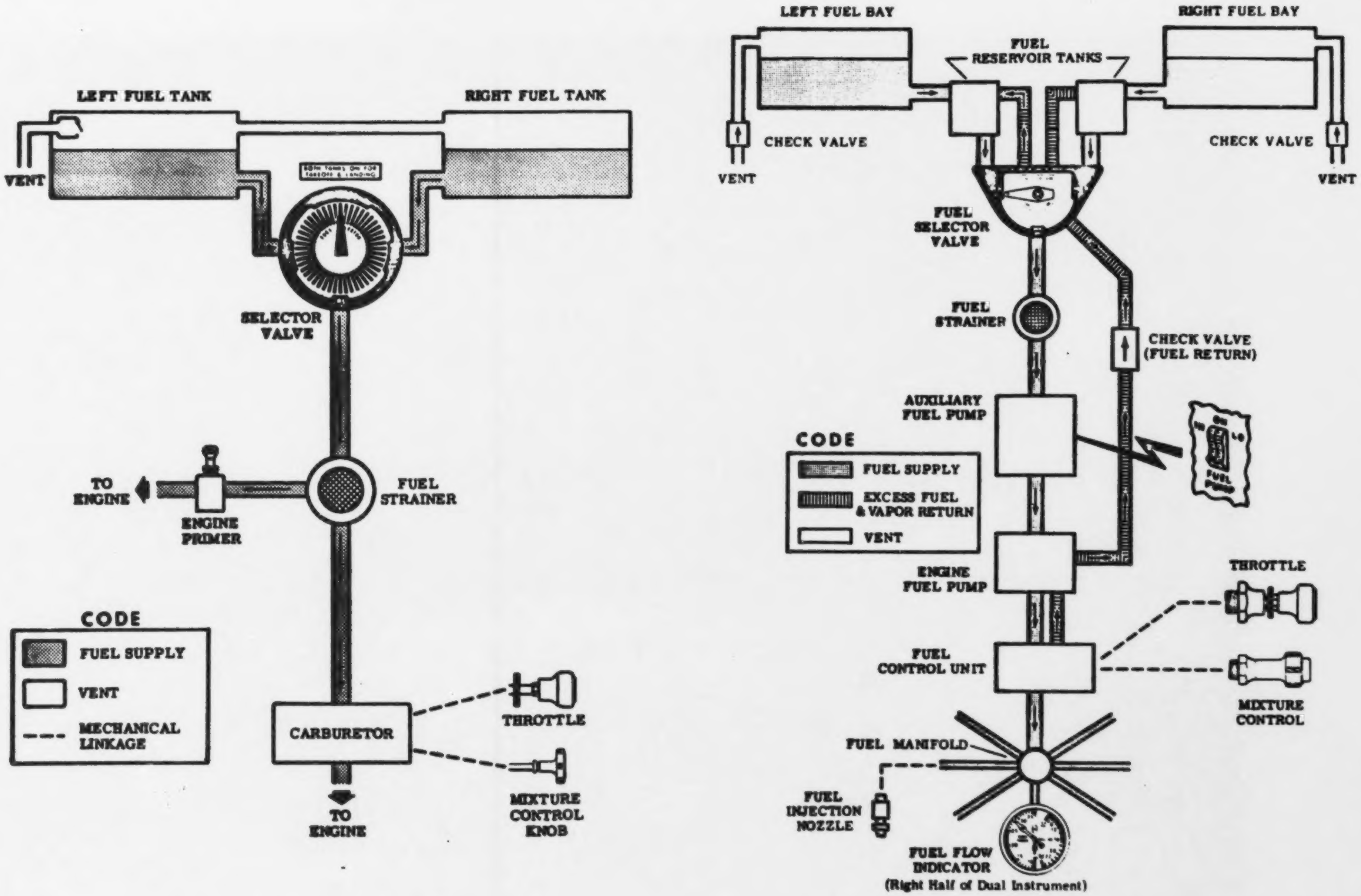
Table 63 - ESTIMATED REDUCTIONS IN AIRCRAFT EXHAUST EMISSIONS ATTAINABLE BY VARIOUS METHODS

	John F. Kennedy International Terminal			
	CO	Organics	NO_x	Particulates
Total emissions in 1967 (lb per day)	66,645	26,441	4,847	1,538
Piston-engine exhaust treatment (a)	-20%	-6%	0	0
Replacement of piston-engine transport aircraft by medium-range fanjets	-18%	-6%	+1%	+2%
Turbine-engine low-smoke combustors (b)	0	0	+?	-50%
Turbine engine annular combustors (c)	-39%	-47%	0	0
Auxiliary ground propulsion (transport aircraft)	-79%	-75%	-16%	-11%
Total reduction by all methods combined	-98%	-90%	~0	-60%

	All FAA-controlled air terminals			
	CO	Organics	NO_x	Particulates
Total emissions in 1967 (tons per day)	2,550	415	43	17
Piston-engine exhaust treatment (a)	-75%	-60%	0	0
Replacement of piston-engine transport aircraft by medium-range fanjets	-63%	-51%	+22%	+23%
Low-smoke turbine-engine combustors (b)	0	0	+?	-50%
Annular turbine-engine combustors (c)	-8%	-17%	0	0
Auxiliary ground propulsion (transport aircraft)	-25%	-34%	-20%	-14%
Total reduction by all methods combined	-85%	-87%	+?	-60%

NOTES:
(a) estimated effectiveness: 90 per cent reduction of CO and organic emission
(b) estimated effectiveness: 50 per cent reduction of particulate emission
(c) estimated effectiveness: 50 per cent reduction of CO and organic emission

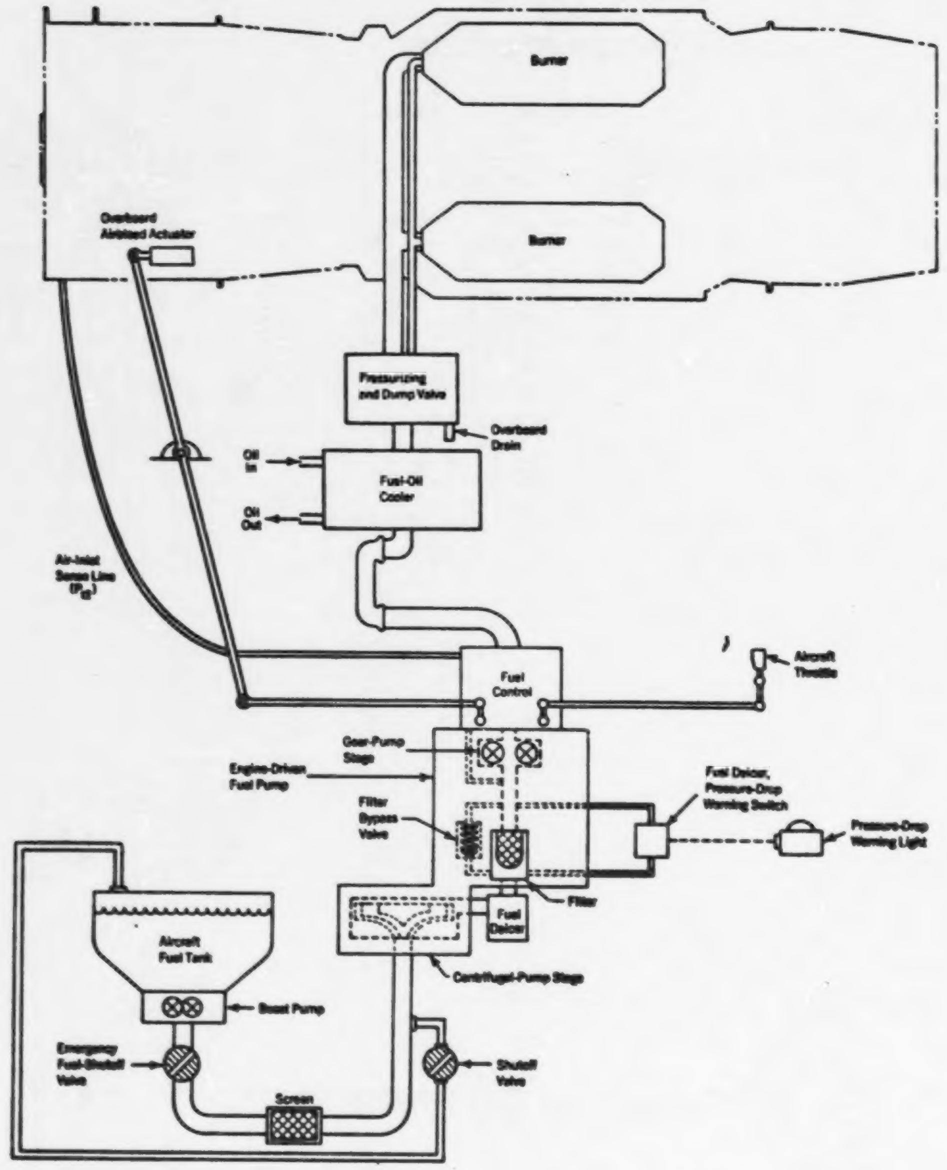
FIGURES


LEFT FUEL TANK
RIGHT FUEL TANK
VENT
BOTH TANKS ON FOR TAKEOFF & LANDING
SELECTOR VALVE
TO ENGINE
ENGINE PRIMER
FUEL STRAINER
CODE
FUEL SUPPLY
VENT
MECHANICAL LINKAGE
CARBURETOR
THROTTLE
MIXTURE CONTROL KNOB
TO ENGINE
LEFT FUEL BAY
FUEL RESERVOIR TANKS
RIGHT FUEL BAY
CHECK VALVE
VENT
CHECK VALVE
VENT
FUEL SELECTOR VALVE
FUEL STRAINER
CHECK VALVE (FUEL RETURN)
AUXILIARY FUEL PUMP
CODE
FUEL SUPPLY
EXCESS FUEL & VAPOR RETURN
VENT
ENGINE FUEL PUMP
THROTTLE
FUEL CONTROL UNIT
MIXTURE CONTROL
FUEL MANIFOLD
FUEL INJECTION NOZZLE
FUEL FLOW INDICATOR
(Right Half of Dual Instrument)

Cessna Model 172 with Lycoming
0-320-E2D Engine

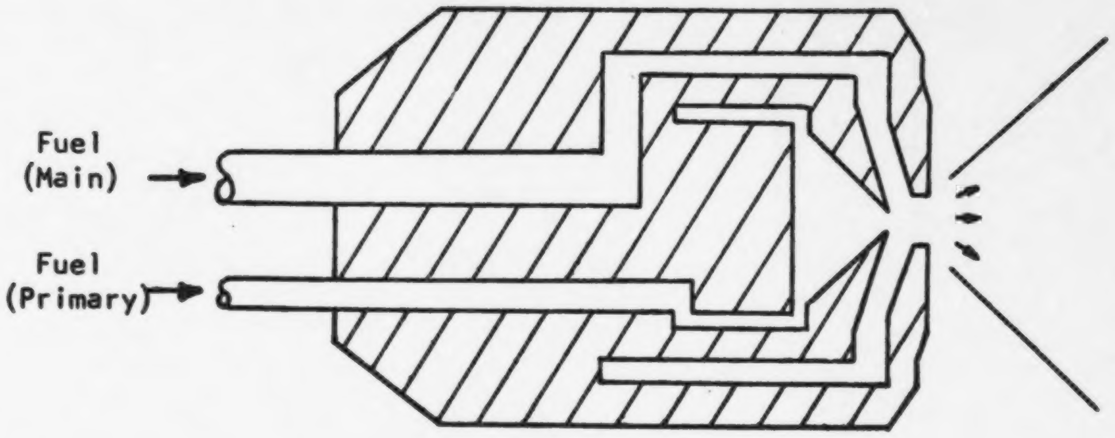
Cessna Model 210 with Continental
10-520-A Fuel Injection Engine

FIGURE 1 - TYPICAL FUEL SYSTEMS FOR LIGHT, PISTON-ENGINE AIRCRAFT
COURTESY OF CESSNA AIRCRAFT COMPANY (REFS 10 AND 11)

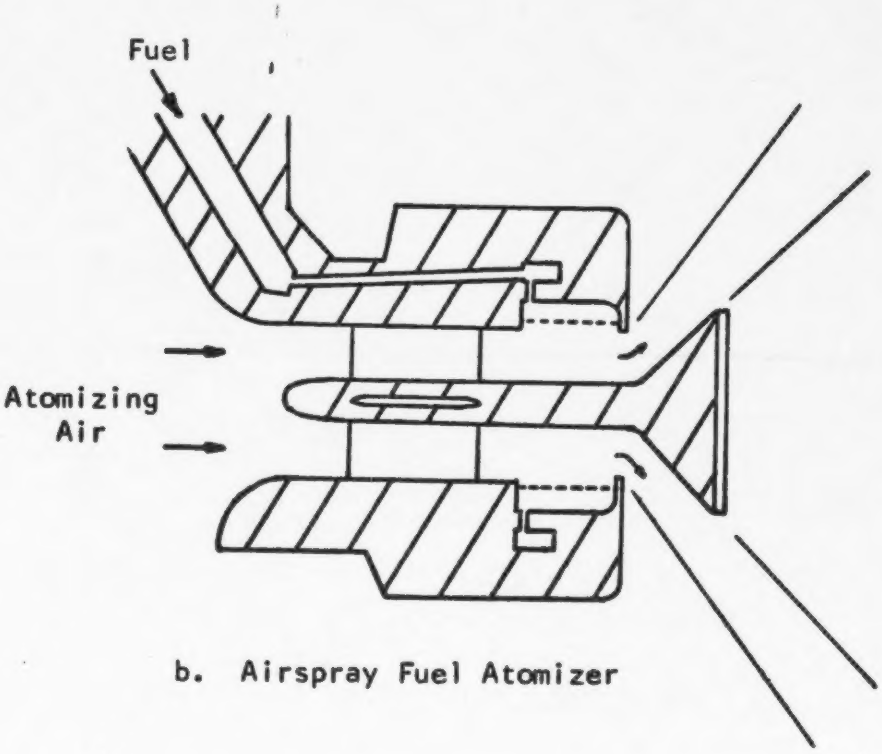

Burner
Burner
Overboard Airbleed Actuator
Pressurizing and Dump Valve
Overboard Drain
Oil In
Fuel-Oil Cooler
Oil Out
Air-Inlet Sense Line (P_{t2})
Fuel Control
Aircraft Throttle
Gear-Pump Stage
Engine-Driven Fuel Pump
Filter Bypass Valve
Fuel Deicer, Pressure-Drop Warning Switch
Pressure-Drop Warning Light
Filter
Fuel Deicer
Aircraft Fuel Tank
Centrifugal-Pump Stage
Boost Pump
Emergency Fuel-Shutoff Valve
Screen
Shutoff Valve

(Reproduced from Reference 9 with
permission of the Hayden Book Co., Inc.)

FIGURE 2 - TYPICAL FUEL SYSTEMS FOR NON-AFTERBURNING TURBINE ENGINE


Fuel
(Main)
Fuel
(Primary)

a. Dual-Orifice Atomizer


Fuel
Atomizing
Air

b. Airspray Fuel Atomizer

(Taken from Reference 13)

FIGURE 3 - TURBINE-ENGINE FUEL INJECTORS

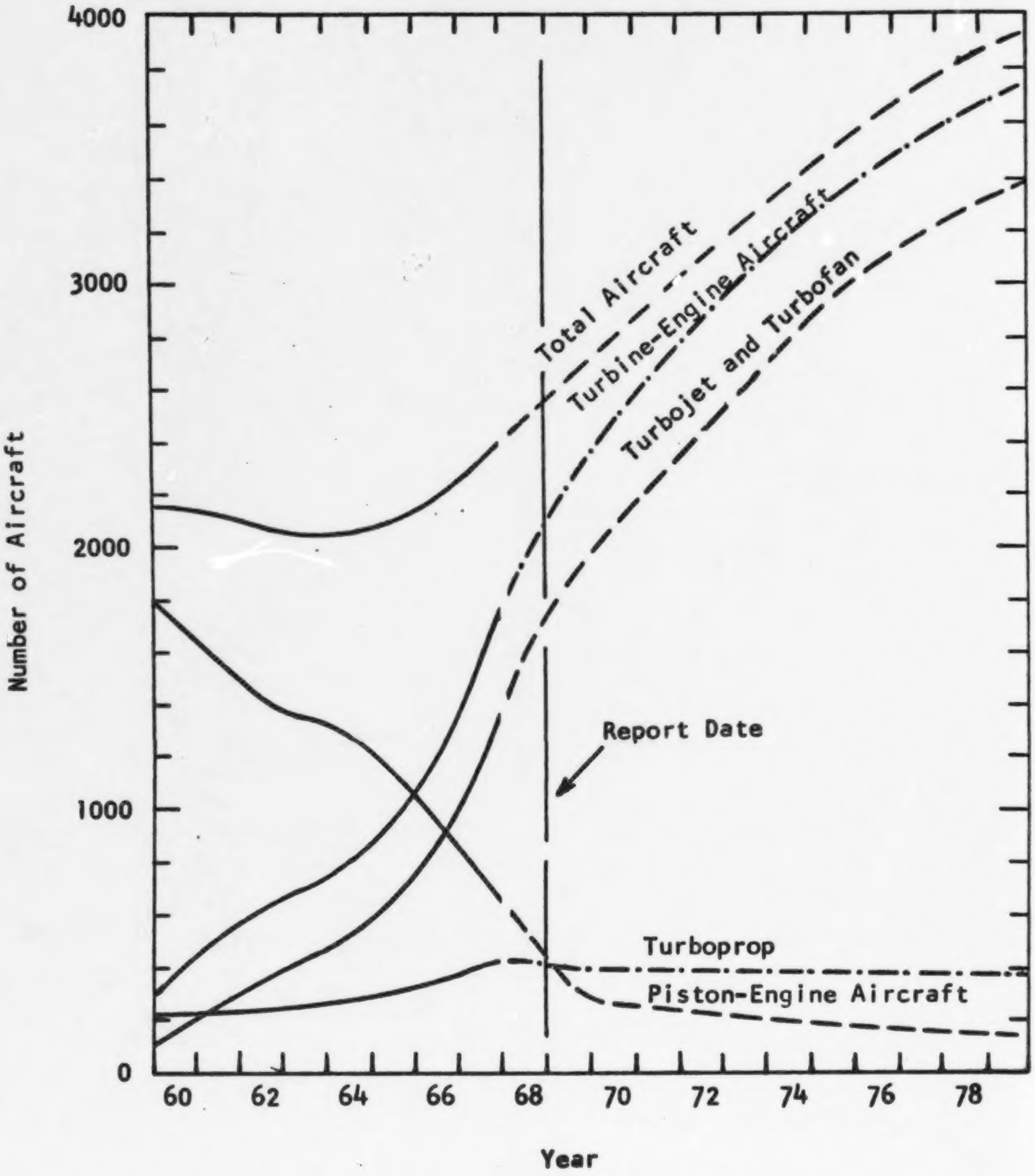


FIGURE 4 - COMPOSITION OF THE UNITED STATES AIR CARRIER FLEET

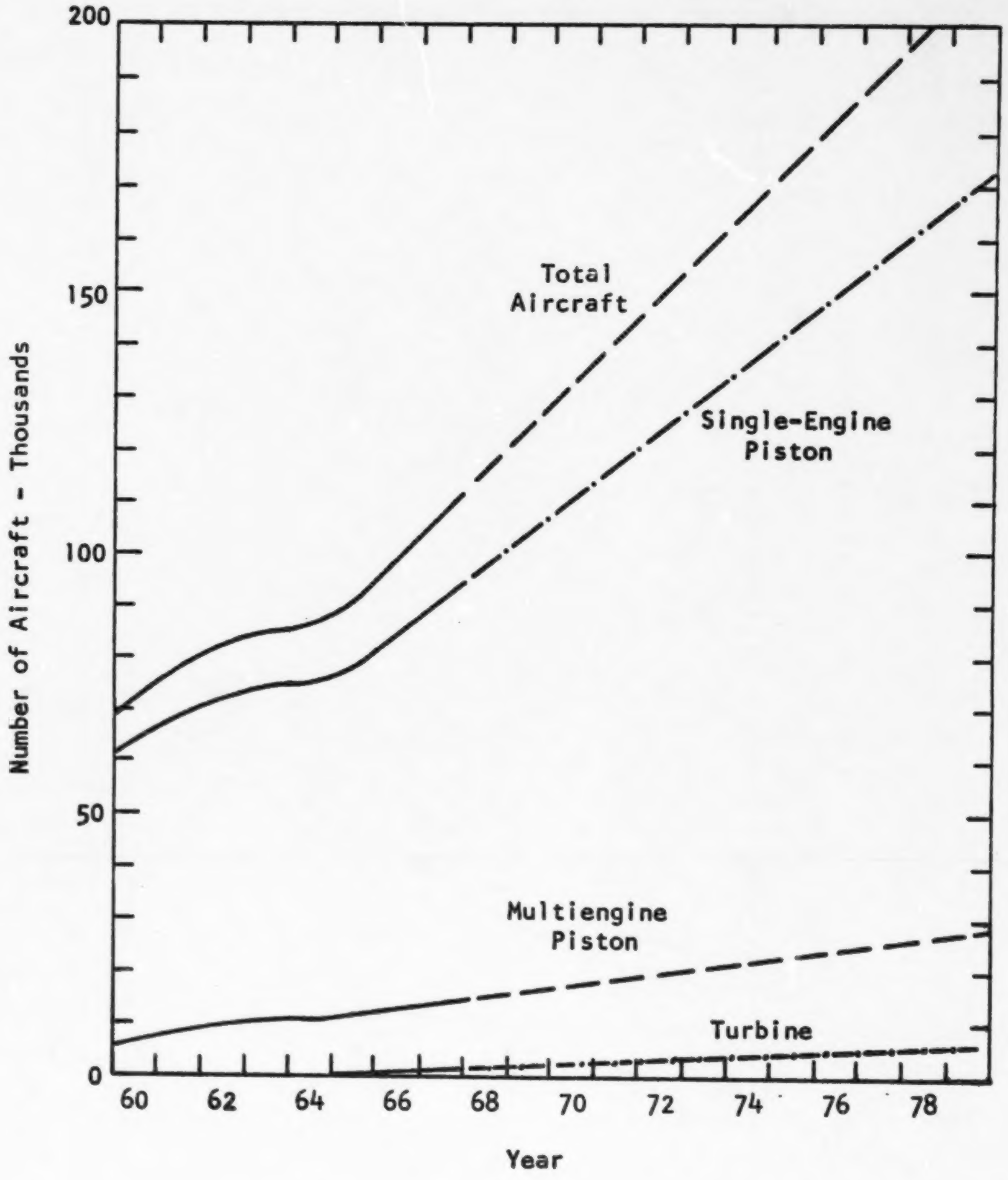
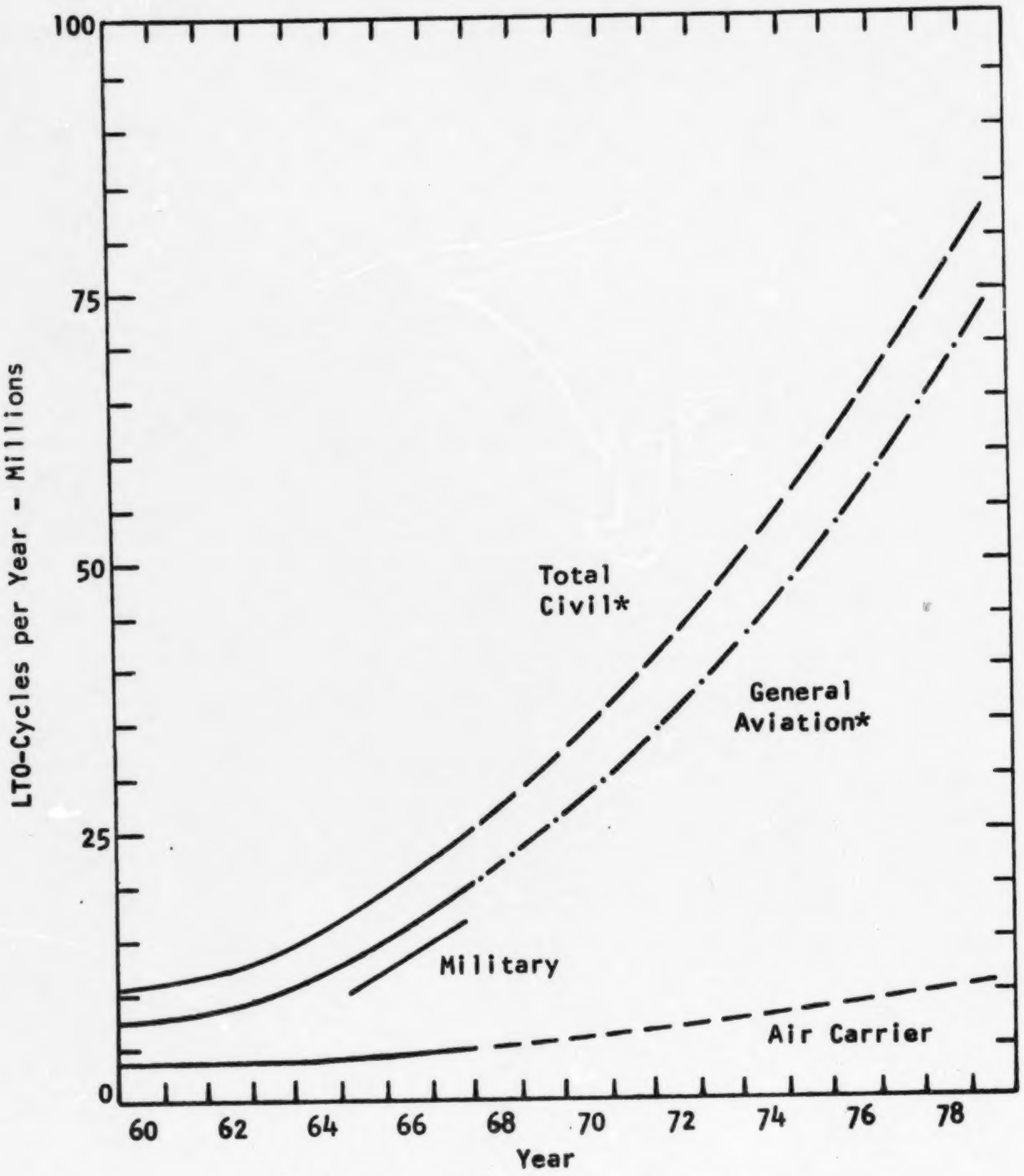
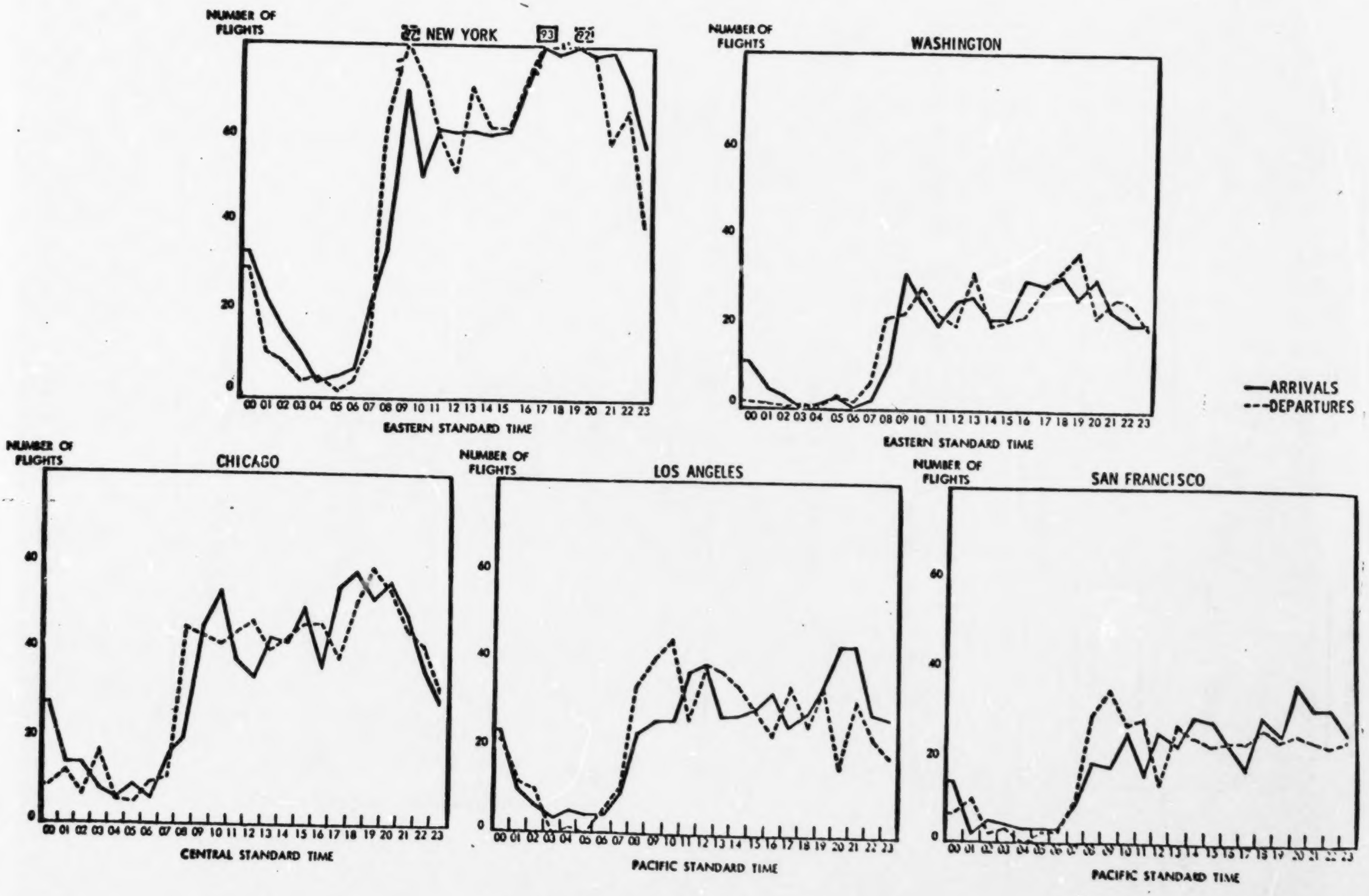


FIGURE 5 - COMPOSITION OF THE UNITED STATES GENERAL AVIATION FLEET



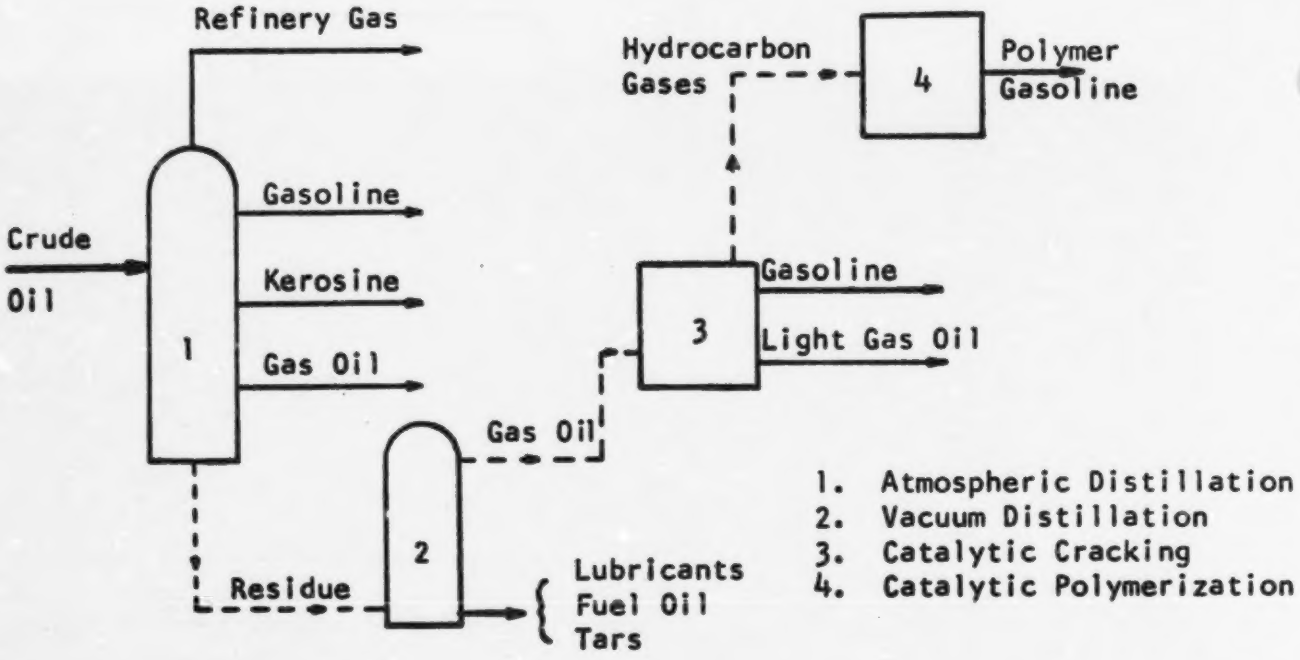
*At FAA-Controlled Terminals Only

FIGURE 6 - ANNUAL AIR TRAFFIC ACTIVITY AT UNITED STATES AIR TERMINALS

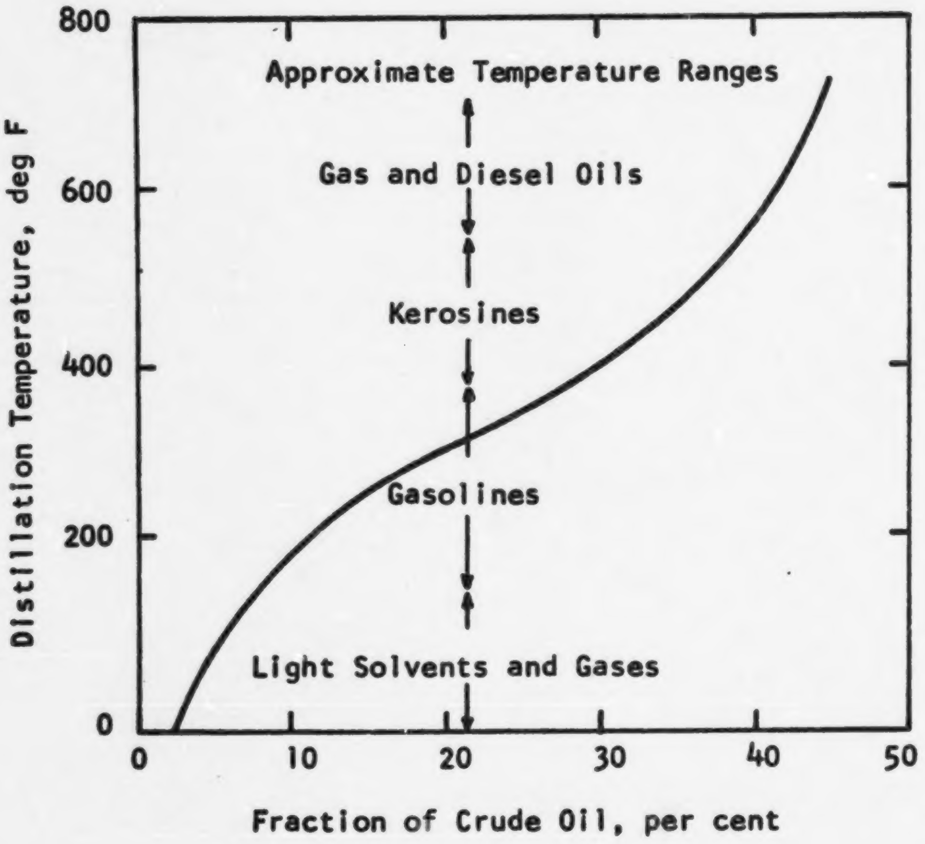


(Reproduced from Reference 31)

FIGURE 7 - HOURLY VARIATION OF AIRCRAFT ACTIVITY IN FIVE METROPOLITAN AREAS - MAY 1967 (SCHEDULED AIR CARRIER AND AIR TAXI ACTIVITY ONLY)

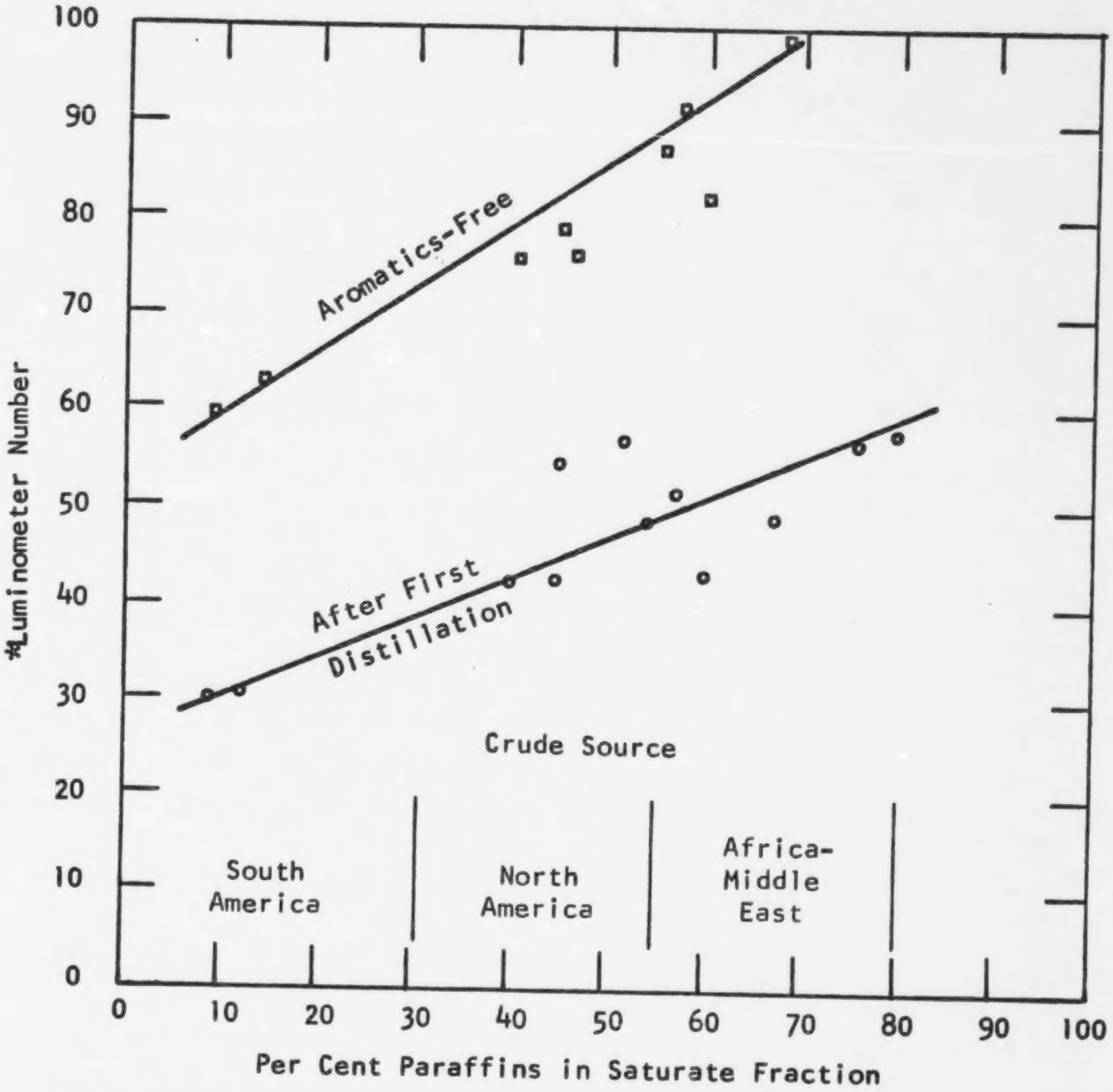

Refinery Gas
Hydrocarbon Gases
4
Polymer Gasoline
Gasoline
Crude Oil
Kerosine
1
Gas Oil
Gasoline
3
Light Gas Oil
Gas Oil
2
Residue
Lubricants
Fuel Oil
Tars
1. Atmospheric Distillation
2. Vacuum Distillation
3. Catalytic Cracking
4. Catalytic Polymerization

a. Process Flow Sheet



b. Products from the Atmospheric Distillation of Crude Oil

FIGURE 8 - PRODUCTS FROM A TYPICAL CRUDE OIL REFINING OPERATION



*Smoking tendancy decreases as luminometer number increases.

FIGURE 9 - LUMINOMETER RATING OF AVIATION KEROSINES AS A FUNCTION OF CRUDE OIL SOURCE (TAKEN FROM REFERENCE 40)

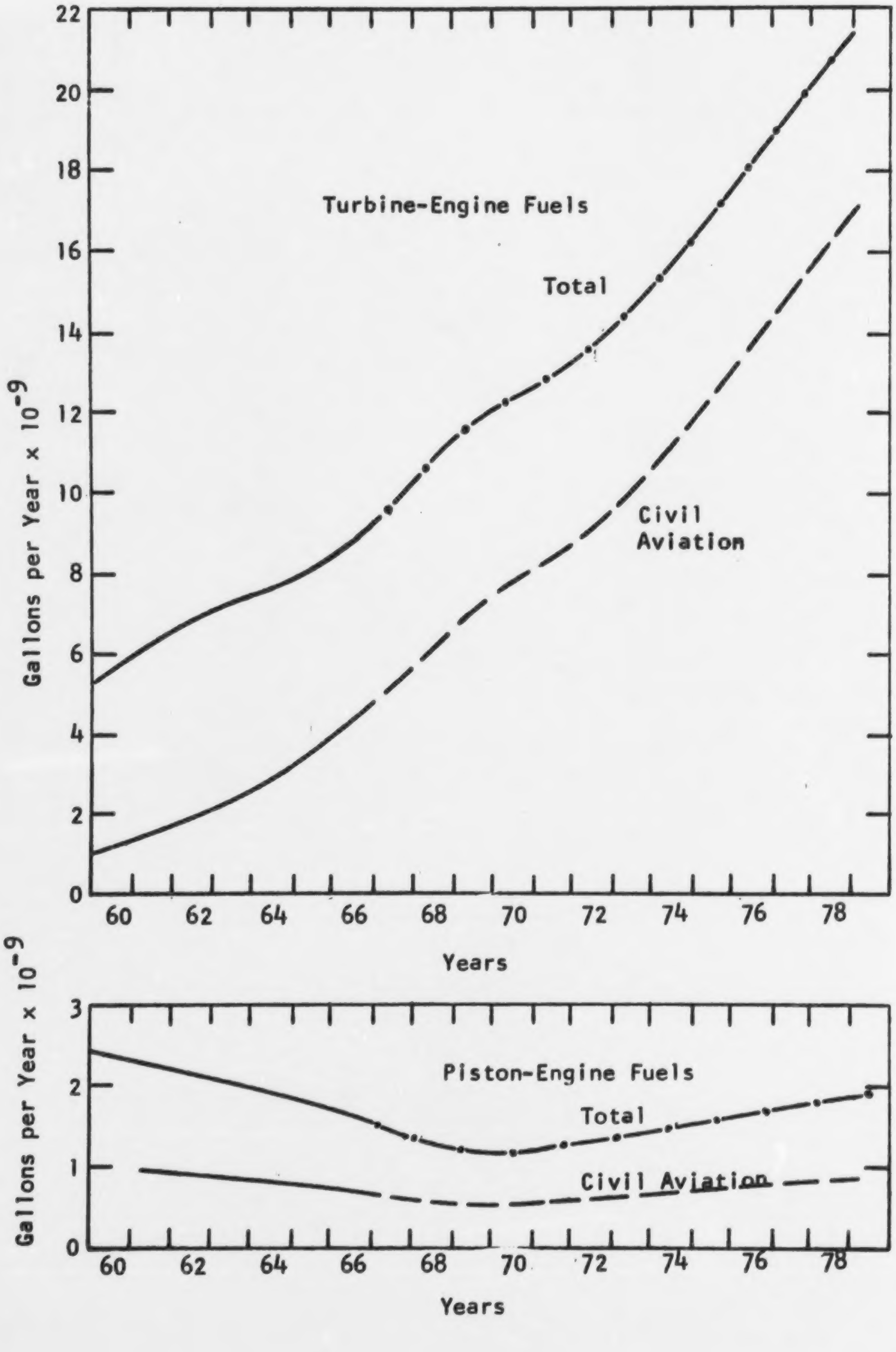


FIGURE 10 - NATIONAL CONSUMPTION RATES OF AVIATION FUELS, YEARS 1960-1979

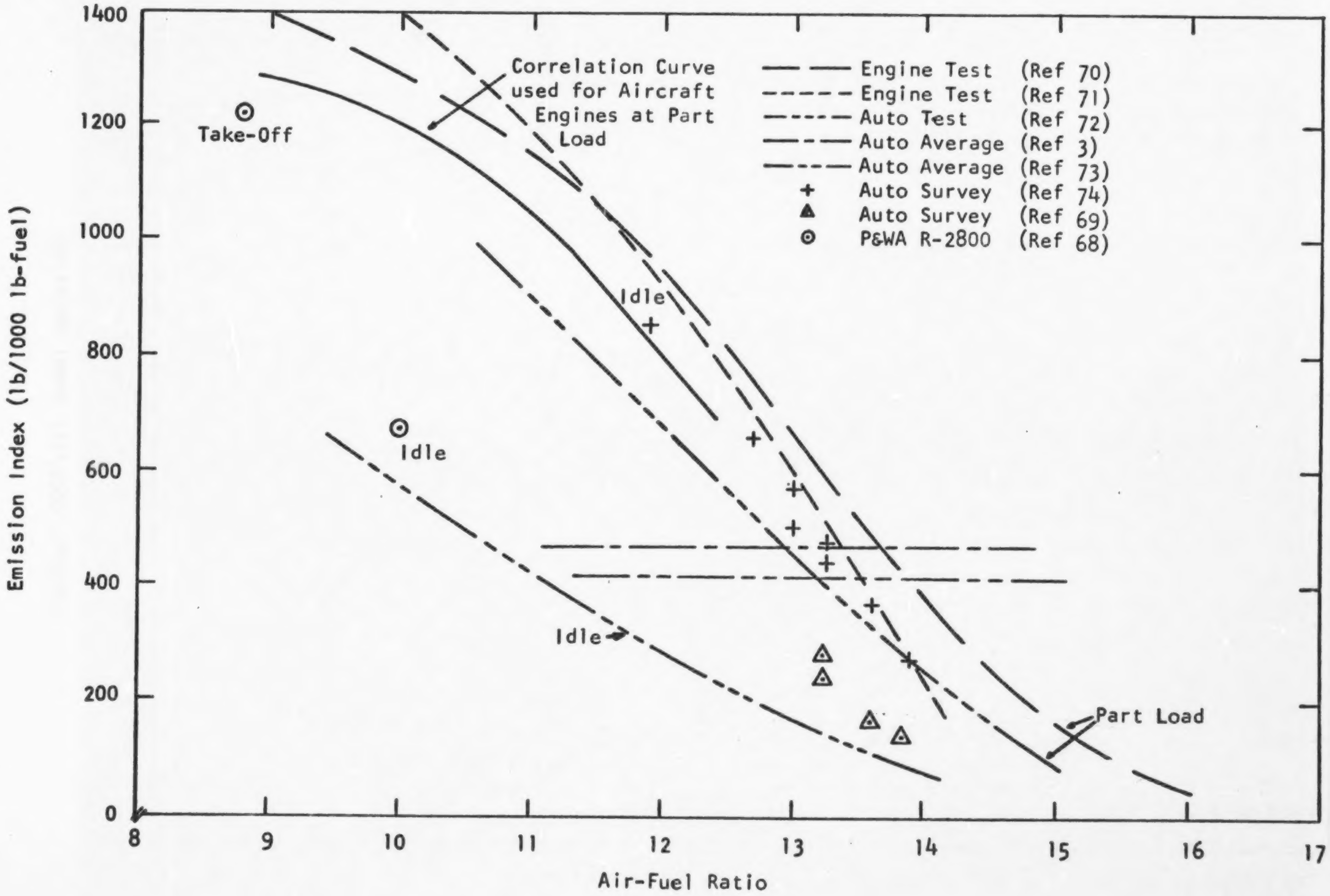


FIGURE 11 - CARBON MONOXIDE EMISSION BY PISTON ENGINES

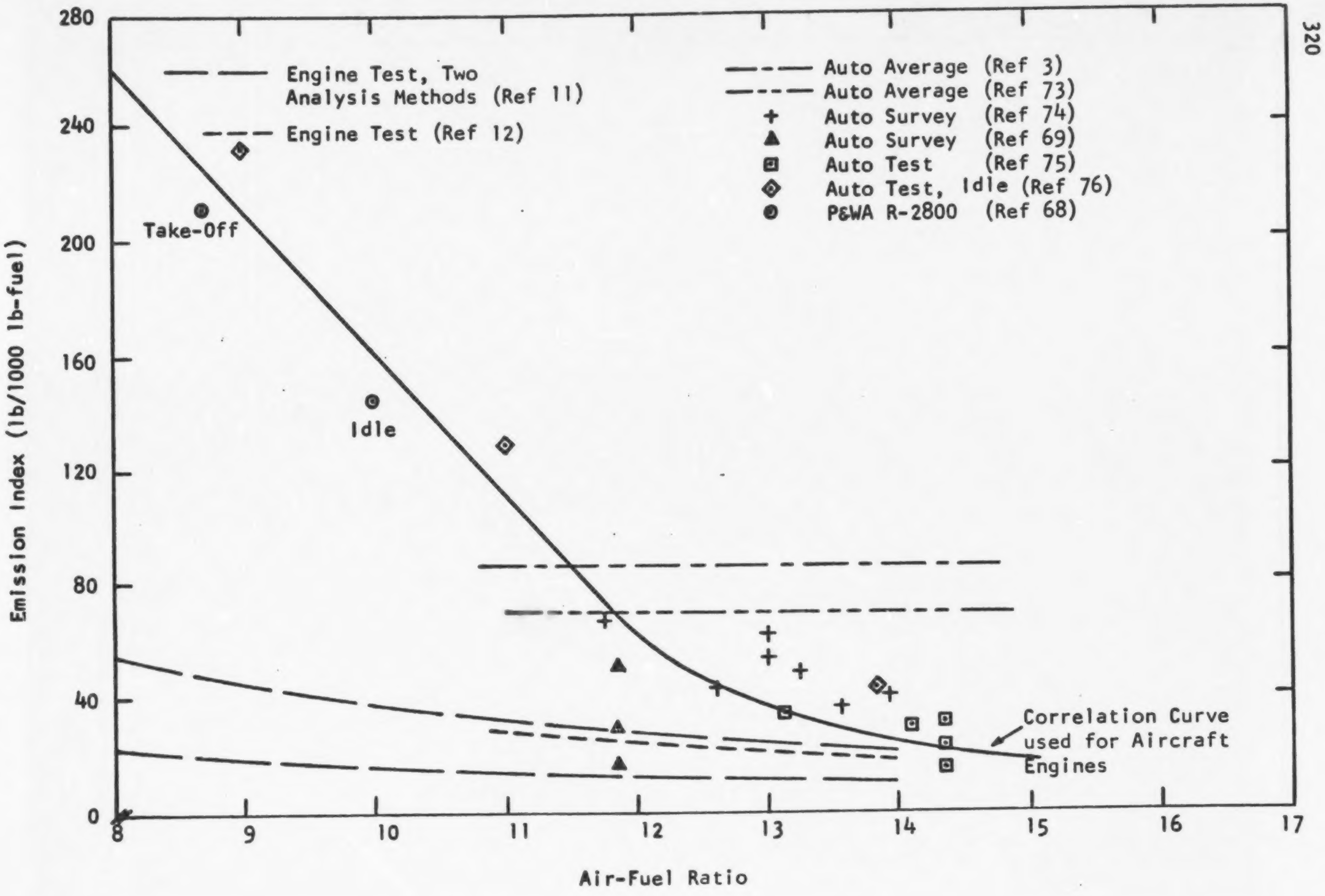


FIGURE 12 - EMISSION OF ORGANICS BY PISTON ENGINES

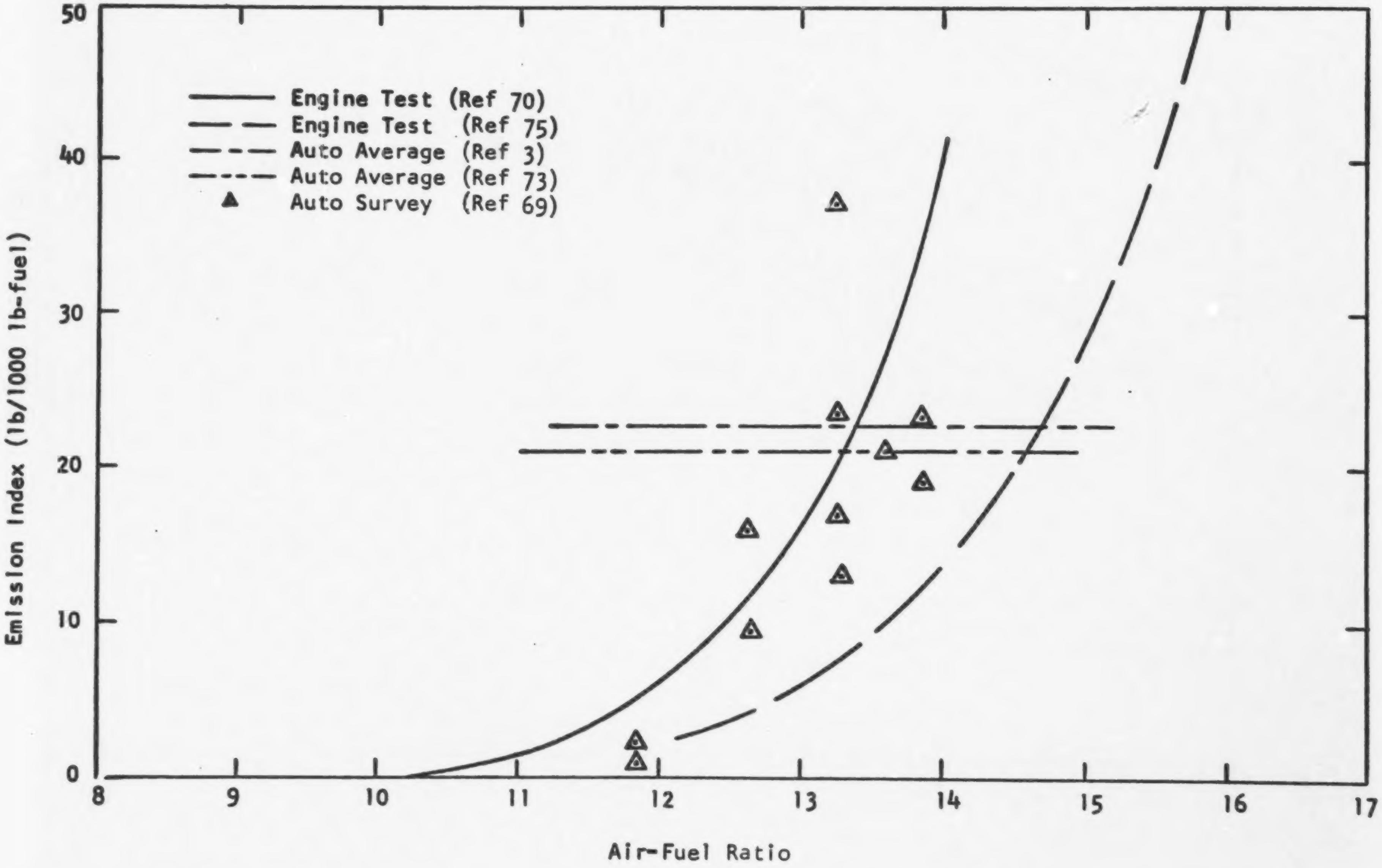
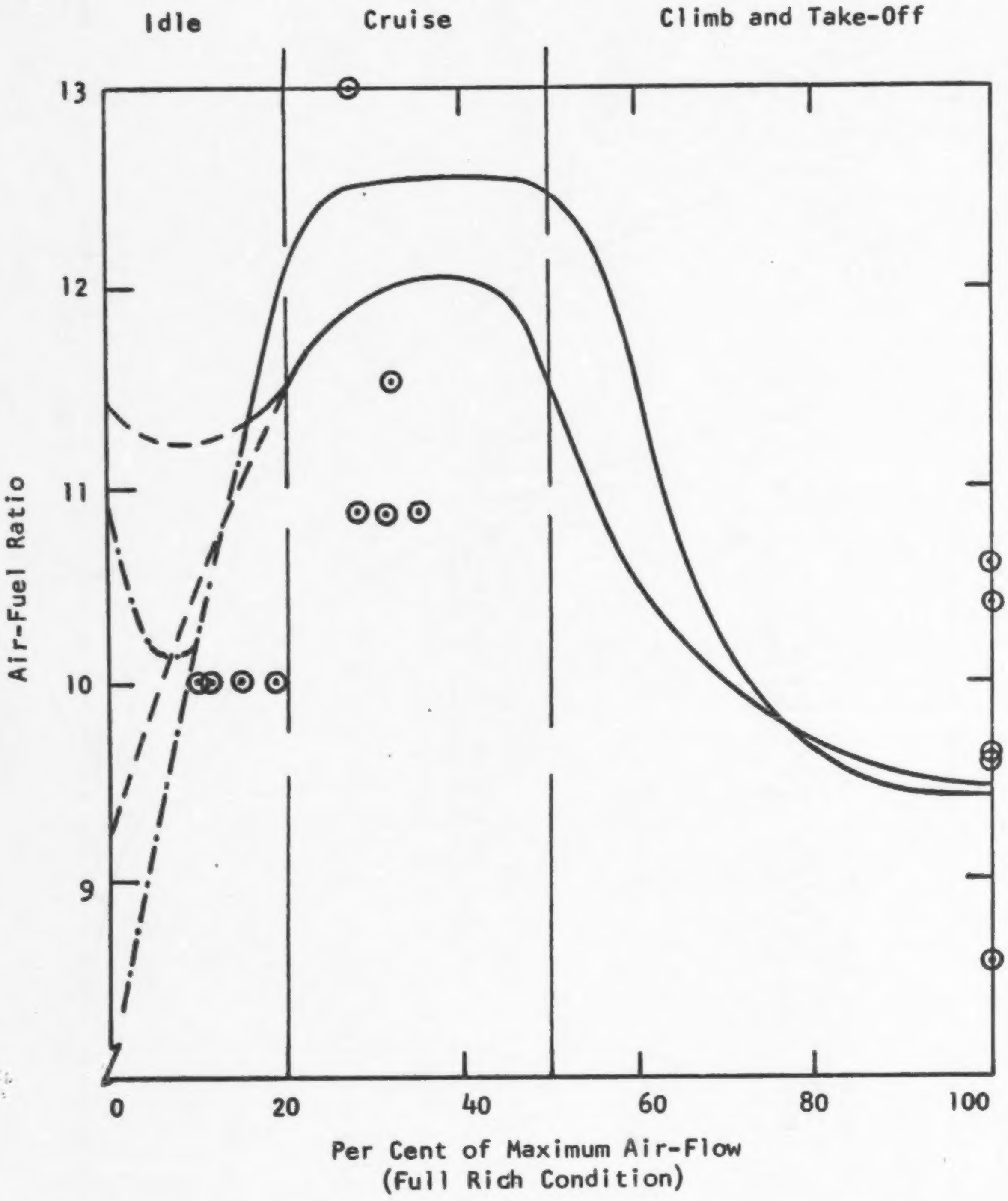


FIGURE 13 - EMISSION OF NITROGEN OXIDES BY PISTON ENGINES



⊙ PWA Data - 5 Radial Engines (Ref 68)
—— Fuel System Performance (Ref 8)

FIGURE 14 - AIR-FUEL RATIO CURVES FOR TYPICAL AIRCRAFT PISTON ENGINES

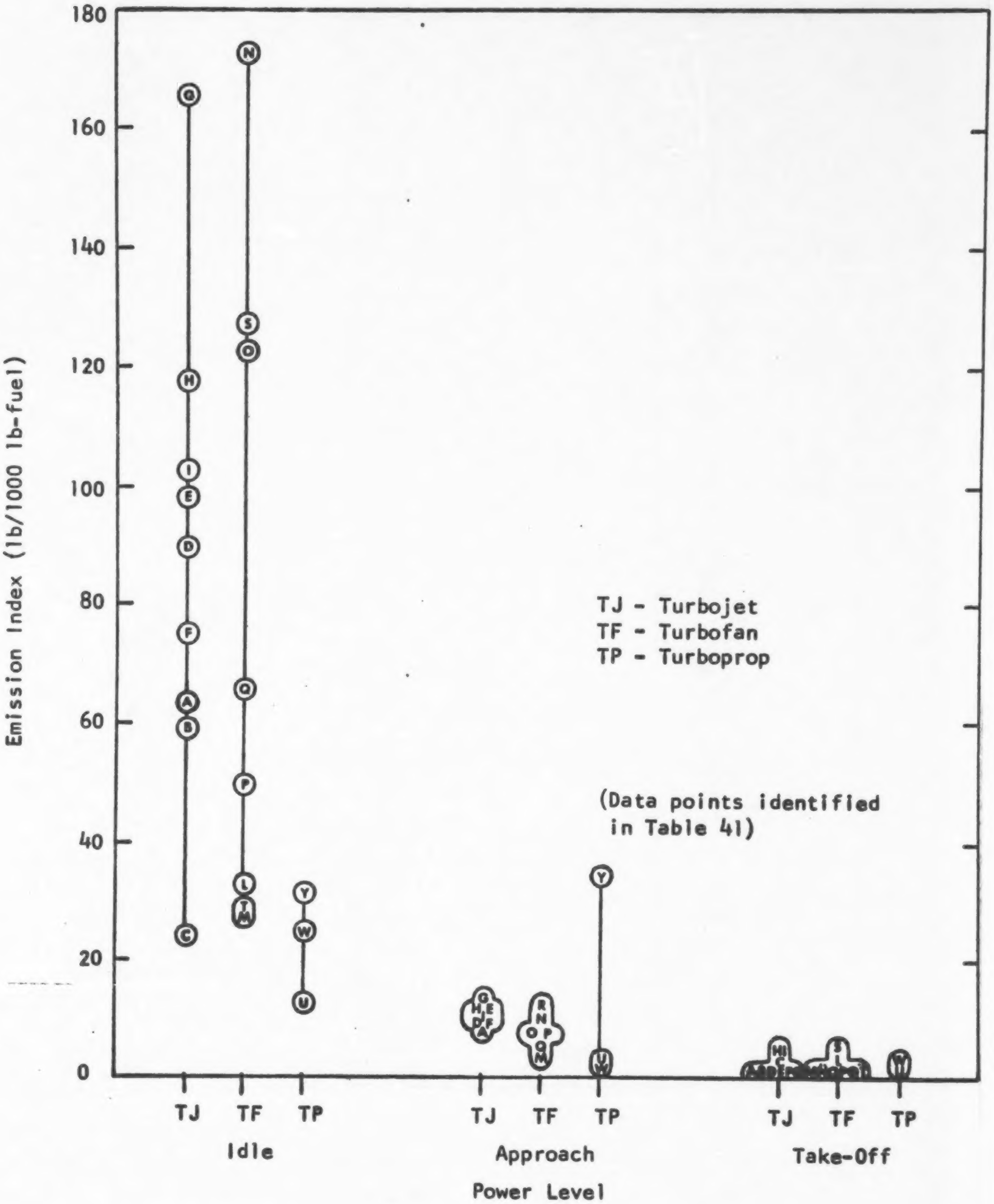


FIGURE 15a - TURBINE ENGINE EMISSION DATA, CARBON MONOXIDE

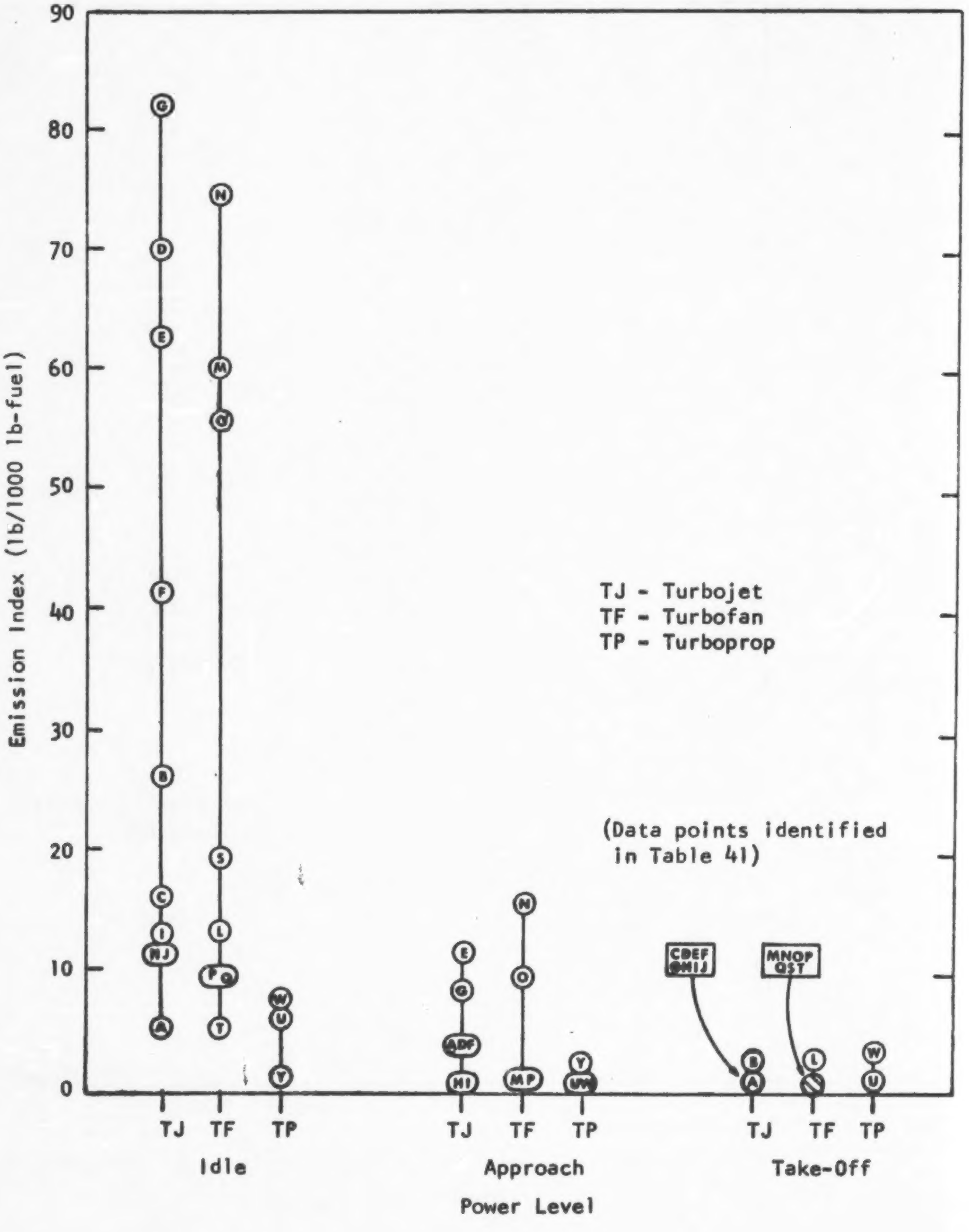


FIGURE 15b - TURBINE ENGINE EMISSION DATA, ORGANICS AS CH_4

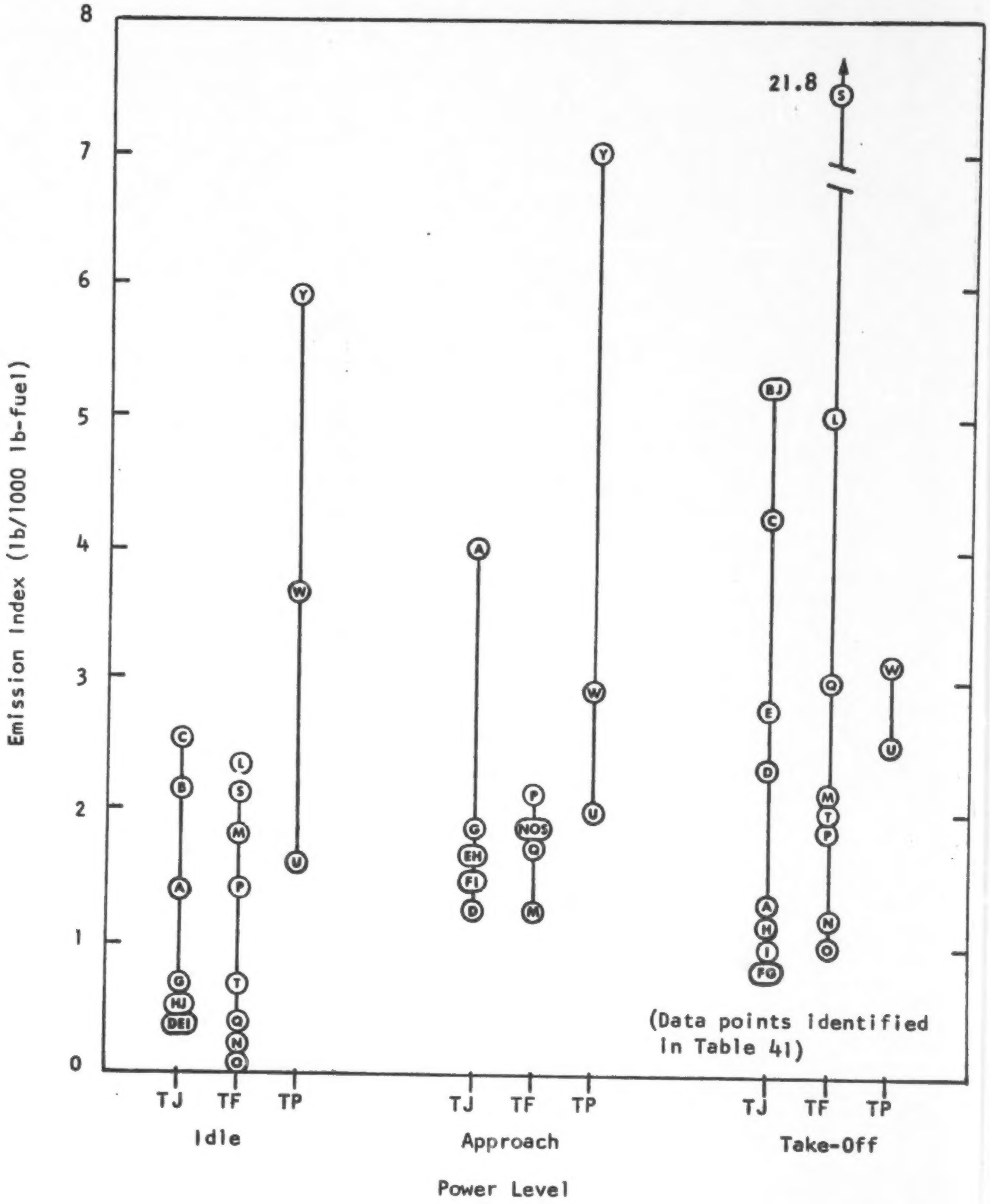


FIGURE 15c - TURBINE ENGINE EMISSION DATA, NITROGEN OXIDES AS NO

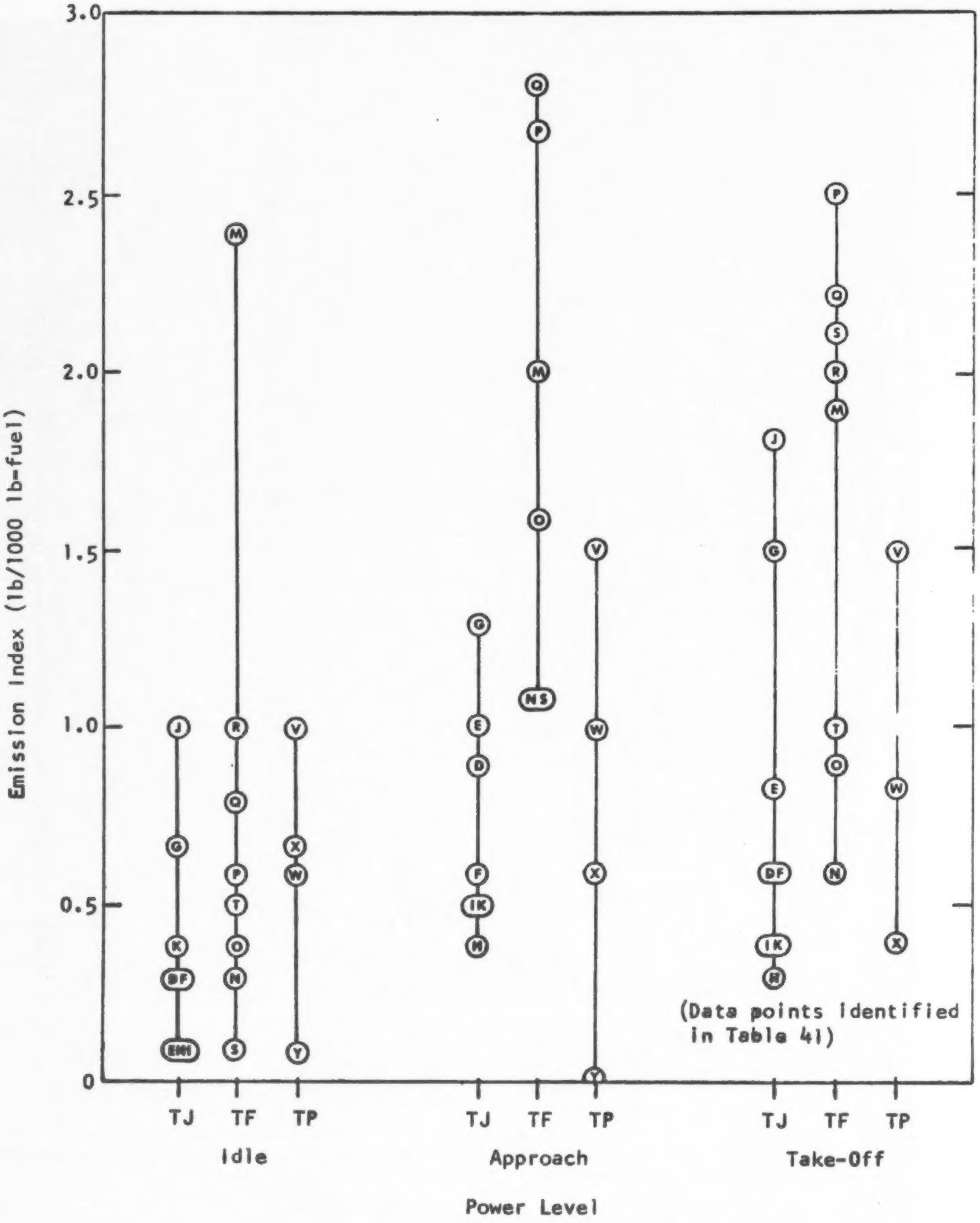


FIGURE 15d - TURBINE ENGINE EMISSION DATA, PARTICULATES

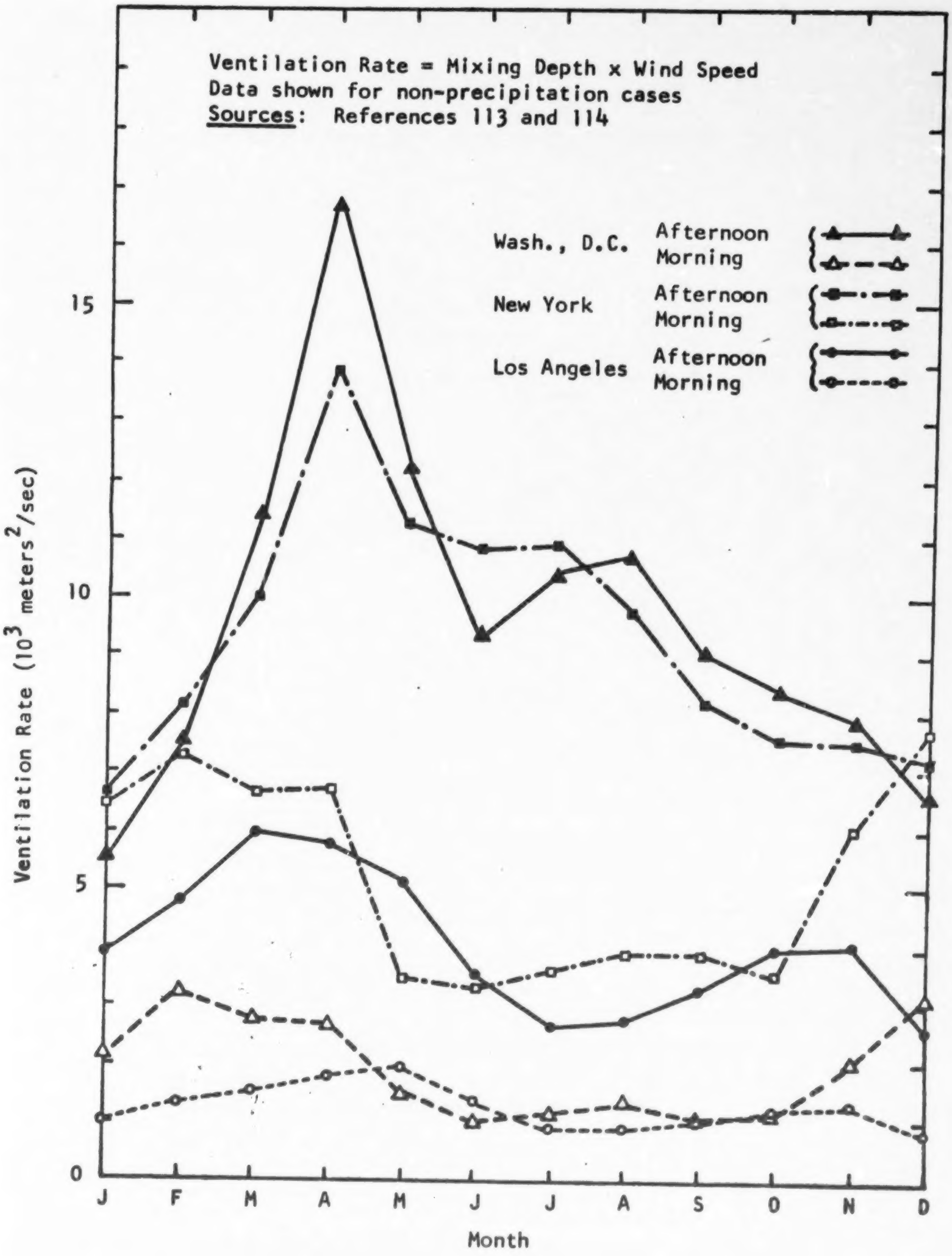
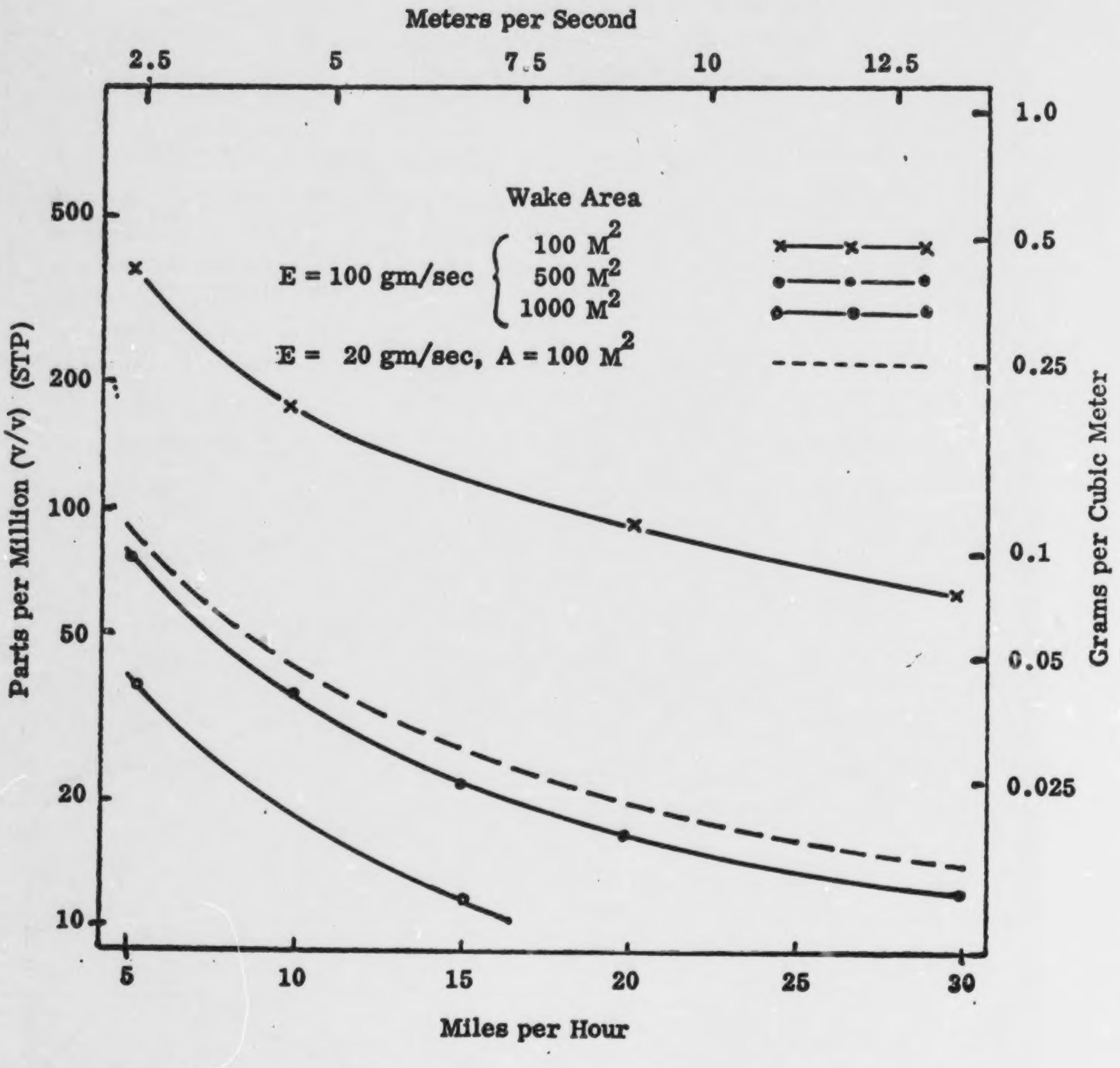


FIGURE 16 - MONTHLY MEAN VENTILATION RATES FOR NEW YORK, WASHINGTON, AND LOS ANGELES



Predictions at various taxi speeds for
Class 1 aircraft (CO Emission = 100 gm/sec)
Class 2 aircraft (CO Emission = 20 gm/sec)

FIGURE 17 - CARBON MONOXIDE CONCENTRATION IN THE WAKE OF TAXIING AIRCRAFT

APPENDICES

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APPENDIX I

SAMPLING AND MEASUREMENT METHODS

Exhaust Sampling Techniques

The measurement of concentrations of pollutants in engine exhaust gases can, in some cases, be accomplished by direct observation of the exhaust gas stream, or by collection of an exhaust gas sample with subsequent analysis of the sample. Direct observation is not commonly used in measuring aircraft engine exhaust emissions. Instead, most measurements, including all those presented in this report, are obtained by analysis of exhaust gas samples.

The primary objective in exhaust gas sampling is obtaining a representative sample of exhaust gas of a known quantity or at a known flow rate. Apparatus used for sampling generally consists of a probe, sampling line, a flow measuring device, a pump capable of drawing the desired flow rate through the system, and collection devices for capturing pollutant samples.

The design of the sampling probe is not critical in measuring concentrations of gaseous pollutants. However, in measuring concentrations of particulates, it is desirable that the probe be designed to achieve isokinetic sampling which is defined as a condition wherein the gas velocity at the sampling inlet nozzle matches the velocity of the stream being sampled. Departures from this condition may cause errors in sampling for particulates whose diameter is greater than 3 to 5 micrometers. However, isokinetic sampling is not considered to be necessary in measuring aircraft engine emission since particulates from these engines are generally less than 1 μm in diameter.

The sampling line, which conveys the gas sample from the probe to the collection and measurement apparatus, must be designed such that no changes in sample composition or physical state occur during transit. The line must be constructed of materials which do not adsorb or react chemically with pollutant materials, and the line must allow free passage of particulate materials. In sampling engine exhaust gases, it is also necessary to maintain the sampling line temperature at a level at which condensation of organic vapors does not occur. This requirement is more severe with turbine engines than with gasoline-fueled piston engines. Turbine engine fuels, which have higher boiling points than gasoline, give rise to organic emissions which also have high boiling points. The requirement for heating the sampling line often is neglected. A notable exception is the sampling technique devised by the Los Angeles County Air Pollution Control District (Ref I-1). With this technique, the entire sampling system is located near the engine so that the sampling line length is minimized.

The design of the sampling pump and flow measuring device usually is not critical since these units normally are installed downstream from the collection equipment. If they are upstream, however, they must also be designed so as not to change the nature of the exhaust gas sample.

The types of pollutant collection devices to be used in a sampling system depend upon the measuring techniques to be employed. Many measuring techniques do not require pollutant collection, but indicate pollutant concentration directly by measuring some property of the gas sample. These techniques are utilized either by connecting the measuring device directly to the sampling system, or by collecting a gas sample in a container (grab sample) and transporting it to the measuring device.

Many other analysis techniques require that the pollutant species being measured be extracted from the gas sample and concentrated in order to determine the concentration of the pollutant in the exhaust gas. These methods of pollutant collection are tailored to the analysis methods with which they are used and are described in the next section.

Methods of Analysis

Particulates

Collection

With particulate analysis techniques which require sample collection, filters or impingers generally are used. These devices effectively separate solid particles from the sample and pass the gaseous components on to other devices downstream. However, if the gas sample contains vapors of low volatility, as is often the case with engine exhaust gases, these vapors may condense in the collecting device and be captured along with solid particulate matter. In this event, the indicated particulate concentration will be greater than that actually existing in the engine exhaust stream, and the organic concentration will be correspondingly less. Vapor condensation can be avoided by maintaining a high temperature throughout the sampling and collecting system.

Mass Analysis

The total mass of particulates is most easily determined by gravimetric analysis. This analysis is performed in two ways depending on the method used for collection. If the particles are collected using a filter paper or cloth bag, the filter is dehumidified and weighted before sampling. After collection, it is dehumidified again and weighed to determine the mass collected. If the collection device is a dry impinger, the collected material is removed from the impinger and weighed directly. If a wet impinger is used, after sampling, the liquid slurry is passed through a pre-weighed, dried, absolute filter. After re-drying it is weighed, yielding a net collected mass. Both of these methods of weight analysis have proven efficient and accurate and will probably continue to be used.

Collected particulates are classified as:

1. Insolubles which are determined by filtering the impinger solutions or, in the case of a dry filter collection, by simply extracting the soluble solids with methyl chloroform and weighing the solid cake retained by the filter paper.
2. Solvent solubles which are determined by weighing the residue remaining after evaporating the combined solvent extract by a stream of dry air at room temperature.
3. Water solubles remaining in the filtrate which are determined by adding water and weighing the residue left after evaporating the filtrate at a maximum temperature of 105 deg C.

Size Analysis

One of the major gap areas in aircraft exhaust emission sampling is in the measurement of discrete particle sizes and particle size distributions. Several techniques which appear to be applicable have not been investigated.

One potential technique is Light Detection and Ranging (LIDAR) (Ref 1-2). LIDAR is basically a tool for remotely detecting the presence and range of particulate scattering inhomogeneities. This capability has been used to measure cloud heights and to detect hazes and fogs. LIDAR has also been used to monitor industrial sources such as smoke stacks. Reagan (Ref 1-3) suggests that LIDAR might be employed to map the dispersal of insecticides dumped from aircraft or to track the airborne flow of wastes released by explosions.

Atmospheric scientists are presently investigating the possibility of using LIDAR in a more quantitative way to determine the quantities of particulates in the atmosphere. Basically the problem involves inverting back scatter measurements to infer the size distribution and number density of the scatterers producing the received signal. Obtaining such information is extremely difficult, however, because a scattered signal depends in a complicated way on several properties of the light scattering medium. This dependency necessitates making certain assumptions relative to the size distribution and index of refraction of the particles. In view of recent experimental results presented by Barrett and Ben-Dov (Ref I-4), it appears that it might be possible to obtain useful estimates of the quantities of particulates in a given volume of gas by making such assumptions.

A second particle counting device which may have application is the Illinois Institute of Technology Research Institute (IITRI) particle counter (Ref I-5). This instrument is a light-scattering, single particle counter which classifies particles into six size ranges from 0.35 to 2.8 μm in diameter. Unfortunately the concentration of particulates issuing from an aircraft engine is higher than the instrument is capable of analyzing. Dilution devices are available which may enable this instrument to operate in higher concentration ranges (Ref I-6).

Gordon and Dennis (Ref I-7) report the successful use of a single stage boundary layer diluter in conjunction with a Royco Instrument Co. PC200 automatic light scattering particle counter when high concentrations of aerosols (0.3-10 μm) are encountered. The results of a series of tests at dilution ratios varying from 5/1 to 353/1 correlate well with simultaneous cascade impactor samples and mass balance techniques.

Gussman (Ref 1-8) reports use of a condensation nuclei counter based on a design by Pollak, that will accurately measure number concentrations in the submicron particle size range. These submicron particles, known as condensation nuclei, are generally considered to be in the size range between 10^{-3} and 1 μm. Because of their size, the nuclei cannot be directly observed. Their presence can be demonstrated by causing them to grow into droplets. This is accomplished by drawing air containing the nuclei into a wet wall chamber and allowing the vapor pressure to reach saturation. When the saturated air is adiabatically expanded to a lower pressure, there will be a drop in temperature dependent on the pressure ratio. At this lower temperature, the air will be super-saturated and the water vapor will condense upon the active nuclei in a matter of milliseconds. Because of the physical nature of the process, the particles all tend to grow to the same final size regardless of their initial distribution. A light beam directed through the chamber onto a sensitive photocell is obscured by the droplets and the degree of obscuration may be calibrated to indicate the number of particles present per unit volume. This type of instrument may also be used to determine the size distribution of the submicron aerosol when the device is used in conjunction with a diffusion battery (Refs 1-9 and 1-10). The diffusion battery is a device which will remove the particles from a flowing air stream with an efficiency dependent upon the particle's diffusional mobility. By operating the battery in accordance with the method of Fuchs (Ref 1-9), it is possible to determine the median diameter and standard geometric deviation of a submicron aerosol distribution.

There are several automatic particle sizing and counting devices available. There are no reports of these types of instruments being used, but, with certain modifications for proper dilution, these devices could be useful in determining the size and quantity of aircraft engine particulates.

Analysis of Light Obscuration Characteristics (Smoke)

Smoke has been defined as the visible by-product of the combustion process. Smoke is a complicated phenomenon and the physical nature of a smoke cloud cannot be defined uniquely by any one parameter. Visibility of smoke results from changes in light transmission, and the parameters which describe smoke visibility have been related in Bouguer's equation (Ref I-11).

There are various techniques, known as stained filter paper systems, for taking smoke samples and indirectly determining a "smoke number". All of these systems have the following common traits. The smoke sample is extracted from the smoke source with a probe, and the sample is transported through a sample line to the smoke filtering instrument. This instrument filters a certain volume of smoke through a selected area of filter paper. (Whatman No. 4 is frequently used.) The mass of carbon collected on filter paper is a function of the sampling volume and the carbon concentration of the smoke sample. The optical density of the stain on the filter paper is related to the quantity of carbon collected per square inch of stain area. Diffuse reflectometers are used to measure the optical density of stains on the filter paper.

Stained filter paper systems presently available include the Bacharach system which is described in detail in ASTM specification

ASTMD-2-156-65 entitled "Standard Method of Test for Smoke Density in the Flue Gases from Distillate Fuels", the Bosch system which is similar to the Bacharach system approved as American Standard Z11.182-1965 by ASA LDC 665.52:662.615.533.1, the Von Brand Meter System, (Reflectance Unit of Dirt System), proposed by Gruber (Ref I-12), and the G. E. Smoke Number System (Ref I-13). A system which uses Millipore filter paper instead of Whatman No. 4 and a proposed smoke number (PSN) is under study by the Aerospace Industries Association (AIA) for standardizing all reported smoke levels.

A technique for estimating smoke density directly by comparing the visual appearance of smoke with a standardized density scale was developed by Ringlemann (Ref I-14). The Ringlemann scale is an accepted smoke density standard for public health service agencies. The scale spans 0.5 units and is used to indicate the light transmission properties of plumes. A Ringlemann number of 0-1 is approximately equal to 80-100 per cent transmission, 1-2 is 60-80 per cent transmission, 2-3 is 40-60 per cent transmission, 3-4 is 20-40 per cent transmission and 4-5 is 0-20 per cent transmission. This technique, although useful, has severe limitations. It is primarily used for black smoke, and the changing background conditions result in errors in smoke density readings.

A method of obtaining plume transmittance by means of contrasting targets also has been used. Luminance measurements are made with a telephotometer on a black target and a white target through the plume and at the side of the plume. The transmittance of the plume is calculated by dividing the difference in luminescence between the black and white targets as measured through the plume by the difference in luminance measured clear of the plume. To date, no satisfactory method has been developed for making this system operational.

Fiorello (Ref I-15) of the Naval Air Propulsion Test Center claims "To date there has been no suitable light transmission or light scattering method found to measure smoke emission of the entire exhaust stream using a direct light transmission and light scattering method through the plume". He describes several methods including a Rolls Royce meter which is a modification of the principle used in the B. T. Hartridge meter. This method does not collect smoke on a filter but draws a sample of gas through a tube, one end of which is a light source and the other end a photocell. Changes in the output of the photocell correspond to the amount of smoke present in the exhaust air sample.

Faitani (Ref I-16) reports the use of an electron microscope in conjunction with a Von Brand reflectance meter to determine the quantity of smoke as well as the particle size.

It appears that the advent of an instrument which will remotely measure the opacity of a jet exhaust is desirable and would enable testing of an aircraft in flight as opposed to one engine mounted in a test cell or on an airplane on the ground. This is a difficult requirement because of the lack of a uniform background, and because of atmospheric density, temperature, and humidity changes which occur with changes in altitude.

Oxides of Nitrogen

There are three commonly used batch methods for the quantitative determination of nitrogen dioxide concentration in a gas sample:

1. The Jacobs and Hochheiser method (Ref I-17) can be used in the presence of high concentrations of sulfur dioxide. Air is aspirated through a fritted bubbler in a sampling train

containing a nitrogen dioxide absorbing alkaline solution. The absorbed nitrogen dioxide is determined colorimetrically as the azo dye. Nitrogen dioxide concentrations of the order of parts per hundred million in air can be determined by this method.

2. Another method used is based on the absorption of nitrogen oxides by a solution of mixed reagent consisting of sulfanilic acid, α-naphthylamine, and acetic acid in a glass bubbler (Ref 1-18). A color is produced which may be compared to standards or observed spectrophotometrically at a wavelength of 550 nanometers (nm). ASTM designation E1607, issued in 1958, is a modification of the above principle, the major changes being the substitution of N-1, naphthylethylene diamine dihydrochloride for α-naphthylene as the coupling agent and the use of a fritted bubbler instead of an ordinary glass bubbler. Again the resultant color can be read with a spectrophotometer set at 550 nm.
3. The third and most commonly used method for the determination of nitrogen dioxide and nitric oxide is the Saltzman method (Ref 1-19). This method is intended for manual determination of nitrogen dioxide in the atmosphere in the range of a few parts per billion to about five parts per million. The sample is obtained by drawing air through fritted bubblers and nitrogen dioxide is absorbed in Griess-Saltzman reagent. A stable pink color is produced and may be read visually or spectrophotometrically at 550 nm. This method is also applicable

to the determination of nitric oxide after it is converted to an equivalent amount of nitrogen dioxide by passage through a permanganate bubbler.

These three methods are batch type analyses which are slow and which do not yield continuous data. Some investigators have incorporated these techniques into a continuous analyzer by using a spectrophotometer and appropriate valving, and these devices do yield continuous results.

Ganz and Kuznetsou (Ref I-20) have developed an automatic recording gas analyzer based on measurement of the PH of a solution which varies with the concentration of oxides of nitrogen in the gas passing through it. It is based on the principle that the interaction of nitrous gases with the absorbent (5% hydrogen peroxide) yields a weak nitric acid solution and that the change in concentration of the acid is dependent on the specific gravity and concentration of gas passing through the solution. Unfortunately the manufacturers do not indicate the sensitivity or specificity of the instrument.

Smith (Ref I-21) describes an instrument to determine NO concentration which utilizes an ultraviolet spectrophotometer technique developed at the University of California at Berkeley. Its accuracy is claimed to be ±10% over a range of 50-2500 ppm and has been used to sample the exhaust from gas turbine combustors.

Nitric oxide and nitrogen dioxide have been measured continuously with a modified Beckman Model K-75 Acralyzer employing modified Saltzman solution. The potassium permanganate solution normally used for oxidizing nitric oxide to nitrogen dioxide is found to result in losses of nitric oxide of up to 50 per cent (Ref I-22). This solution may be replaced with a tube containing chromic oxide impregnated glass fiber filters which oxidize essentially 100% of the nitric oxide. A cold trap is inserted prior to the oxidizer to prolong its life. In addition, the N(1-naphthyl) ethylenediamine hydrochloride NEDA normally used as the coupling compound is replaced with N(1-naphthyl, acetyl) ethylenediamine (ANEDA). The former reduces approximately 10% of the nitrogen dioxide to nitric oxide, thus giving low results for nitrogen dioxide and high results for nitric oxide. This reduction is only 1-2% with ANEDA. The absorbtances of the resulting solutions are measured with a Bausch and Lomb Spectronic-20 spectrophotometer.

Carbon Monoxide

The quantity of carbon monoxide found in the exhaust of a jet engine is very low compared to other sources such as the piston engine. This fact negates the use of an Orsat type analysis, which is a widely used technique for measuring high concentrations of CO, CO_2 and O_2 in gas streams.

Several methods are presently available for quantitatively analyzing the carbon monoxide content in a gas sample. One of the most common and least expensive tools is the carbon monoxide indicator tube. When highly purified silica gel, impregnated with ammonium molybdate and a solution of palladium or palladium oxide, is digested in sulfuric acid, it forms a silicomolybdate and upon being exposed to carbon monoxide forms a molybdenum blue. The depth of color in the detector tube varies from faint green to a deep blue in proportion to the amount of carbon monoxide present in the air being sampled. This method has been used on a continuous basis for sampling carbon monoxide in the range of 1:2 parts per million by aspirating a metered flow of air through the tube at a constant rate and observing the change of color with respect to time. It has been used for sampling aircraft jet engine exhaust with some degree of success (Ref I-1).

An instrument often used for monitoring carbon monoxide is a pressurized, non-dispersive, infrared (NDIR) spectrometer. This instrument has been used in studies by the National Air Pollution Control Administration (Ref I-23). The instrument is a selective non-dispersive type infrared analyzer comprising a source of radiation, a beam chopper, sample and comparison, a beam combiner, a detector, preamplifier, control box, and readout. It is in wide use for the monitoring of carbon monoxide and is considered to be reliable and accurate.

In an NDIR analyser, two Nichrome filaments are used as sources of infrared radiation. Beams from these filaments pass through parallel gold-plated stainless steel cells. One beam traverses the sample cell, and the other a comparison cell. The emergent radiation is directed into the signal detector cell. As the gas in the detector absorbs radiation its temperature and pressure increase. An expansion of the detector gas causes a condenser microphone membrane to move. This movement, when converted and electrically amplified, produces an output signal.

Between the source and the cells, a semicircular beam chopper alternately blocks the radiation of the sample cell and the comparison cell. When the beams are equal, an equal amount of radiation enters the detector from each beam. The amplifier is tuned so that only variations in light intensity occurring at the desired frequency produce an output signal. Therefore, when the beams are equal, the output is zero.

When the gas to be analyzed is introduced into the sample cell, it absorbs infrared energy and thus reduces the radiation reaching the detector from the sample beam. As a result, the beams become unequal and the radiation entering the detector pulses as the beams are alternated. The detector gas expands and contracts in accordance with the pulse and causes the membrane to move in response. The membrane movement varies the condenser microphone capacity and the variation in capacity generates an electrical signal which is proportional to the difference between the two radiation beams. The signal is then amplified and fed to an indicating meter.

This type of device may be specifically sensitized to a single component in a multi-component stream. Normal variations of background components generally effect analysis signals less than one per cent of full scale range.

Scott (Ref I-22) reports the use of a Beckman Model 513AL Non-Dispersive Infrared Analyzer to monitor carbon monoxide continuously in the range of 0-50 ppm. This analyzer contains an optical filter to eliminate the interference from atmospheric moisture which will otherwise produce high readings.

Scott also utilizes an Aerograph Model 1532-2B Chromatograph with dual helium ionization detectors. This instrument is used to verify the results from the infrared analyzers measuring carbon monoxide. The instrument is claimed to determine carbon monoxide concentrations to plus or minus 0.1 ppm in the 0.0-10.0 ppm range and to plus or minus 1 per cent of the component value from 10-100 ppm. It has an ultimate capability of detecting as little as 1 ppb carbon monoxide. This sensitivity is not required for aircraft analysis but the accuracy of ±1 per cent is a great asset. Both of these instruments are calibrated with "close tolerance", pre-analyzed gas mixtures.

A spectrophotometric method has been used which relies on the reduction of a silver salt of an acid to give a sol. This method is claimed to be very sensitive and possibly has an application in jet exhausts (Ref I-24). Another method from the same source is an electrochemical method utilizing the oxidation of carbon monoxide at a vibrating electrode in a solution of borax.

A type of wet chemical analysis using iodine pentoxide is generally not sensitive enough for measuring the concentrations of carbon monoxide found in the ambient atmosphere and can be used only when the levels are sufficiently high as in piston engine exhaust analyses (Ref I-24).

Wilson (Ref I-24) reports a simple but precise instrumental method which makes use of the temperature changes in the air stream when carbon monoxide is oxidized over a catalyst. This method is useful when a continuous monitor is desired. The problems of measuring a small temperature rise may be complicated, however, in an engine exhaust by the high temperatures already present.

Carbon Dioxide

Several methods are currently available for monitoring carbon dioxide, both on a continuous and a batch basis. One of the most common methods presently in use is the Orsat type analysis. This is a batch analysis method which has been applied successfully to exhaust sampling in stationary engines (static tests) (Ref I-23).

Workers at Pratt and Whitney Aircraft have reported the use of a gas chromatograph for measuring the volume of CO_2. This device also measures O_2, CO and CH_4. This method requires a grab sample which has an inherent drawback in that the sample must be analyzed within a short period of time after collection due to CO_2 diffusion to the walls of the exhaust gas sample container.

High range CO_2 detection tubes also have been used at Pratt and Whitney Aircraft with some degree of success as indicated by comparison with the chromatographic method. Although this testing was on a batch basis, it is felt that by constant aspiration a continuous sample could be obtained and analysed.

Wilson (Ref I-24) speaks of Parsons' use of an interference filter photometer at 4,290 μm to continuously measure CO_2 in the 1% - 18% range. This technique has been applied in the analysis of the CO_2 in the exhausts of motor vehicles.

CO_2 can also be monitored using a non-dispersive infrared analyzer. This is an accurate, continuous device which utilizes the principle of infrared analysis to monitor carbon dioxide down to 1-2 ppm (see previous section).

There are several other techniques available for the quantitative measurement of carbon dioxide in the ambient atmosphere, but in general, these methods are used for measuring minute quantities of carbon dioxide. This does not preclude the use of a dilution device to enable these techniques to be applied, but the techniques already described fulfill the analysis requirements.

Organic Compounds

In this report, a distinction is made between hydrocarbons and other organic compounds. Saturated hydrocarbons are not very reactive and many of the reactions described in the literature as involving "hydrocarbons", actually occur with oxygenated organic compounds or with unsaturated or aromatic hydrocarbons.

Total Organic Measurements

George and Burlin (Ref I-1) report collecting gas samples in evacuated two-liter glass flasks. The gases were analyzed with an infrared spectrophotometer at the 3,450μm wavelength absorption band.

Lozano (Ref I-23), while monitoring jet engines of various types in a test cell, continuously monitored organics with a flame ionization detector.

Jacobs (Ref I-18) reports the use of a selective, nondispersive type, infrared analyzer which can be used to determine the organic concentration in the atmosphere. The instrument is calibrated using hexane, and the results obtained must be interpreted in this light. This instrument has been successfully adapted for use in the measurement of organics emitted from jet engines.

Total organics have been monitored with Beckman Model 108A and 109A flame ionization detectors, and Williamson (Ref I-2) reports the use of a flame ionization detector for use in measuring total organics on an automatic basis. This device operates on the principle that a pure hydrogen flame burning in air produces a negligible quantity of ions while oxidized organics produce large quantities. The number of ions produced bears a direct relationship to the number of carbon atoms present in the sample. The ion charged flame is placed in an electric field which permits ion collection. The resulting electric current is recorded. Williamson's major contribution was in automating the system to enable continuous analyses every 30 seconds by use of intricate manifolding, timing, valving and analyzing systems.

Specific Organic Measurements

A Perkin-Elmer Model 900 Gas Chromatograph with dual flame ionization detectors and a sub-ambient temperature accessory has been used to analyze for individual organics (Ref I-22). The separation of the components is accomplished with a 150 ft by .01 in ID column coated with Versalube. The sample is concentrated directly on the column at -65°C or lower. Linear temperature programming is used to elute all individual organics from C_1 to C_{10} in less than 45 minutes. The sensitivity is less than one part per billion (ppb). An electronic digital integrator-printer is used to tabulate the concentrations of the 150-200 peaks (compounds) which result from each sample injection. Some of these peaks are not immediately identified but their organic class may be determined by subtractive techniques. This method is recommended for exhaust analysis by the Coordinating Research Council.

McEwen (Ref I-25) reports the use of a gas chromatograph for analyzing organics in automobile exhausts which also appears to be applicable to aircraft emissions. This method was developed to analyze the complete range of organics in both raw and highly diluted exhausts. A commercial chromatograph was modified to include a separate oven for thermostating a gas sampling valve and a flow switching valve, a subtractor column for removing unsaturated hydrocarbons, and an absorption column in dual arrangement with a capillary column. Exhaust gases were analyzed successfully at all operating modes. This technique is similar to that reported by Scott (Ref I-22)

Korth (Ref I-26) reports the use of a programmed chromatographic technique for analyzing the exhaust emissions from a gas turbine automobile with success.

Klosterman (Ref I-27), in investigating the organics found in automotive exhausts, approached the problem with a simple analytical method by adapting existing organic analyzers so that the resulting system analyzes classes of compounds in groups according to their reactivity in the atmosphere. In Klosterman's method, a sample of dilute automobile exhaust is passed through a system of scrubbers to remove components selectively. One column removes olefins, and another removes olefins and aromatics except benzene. By subtraction from the total, the organics are reported according to reactivity class. The scrubber system is external to the analyzer and no modification of the instrument is required. A flame ionization analyzer was used for measuring total organics. An automatic cycling timer was incorporated to regulate the several components of the analysis.

Polynuclear Hydrocarbons

Polynuclear hydrocarbons are a group of polycyclic hydrocarbons, some of which have been shown to have carcinogenic properties. Considerable interest has been expressed in the determination of the amount of such substances in the air. There are three commonly used methods for determining concentrations of polynuclear hydrocarbons. Most of the methods used involve sampling of air by absorption or condensation techniques.

One method, the Quinon test developed by Sawicki and Miller (Ref I-28), is a color test for the detection of polycyclic compounds. A brilliant dark blue color is obtained with pyrene and benzo(a)pyrene and the concentration is determined by prior calibration.

A second method reported by Jacobs (Ref I-18) is the benzal chloride test. Lipmann and Pollack noted many years ago that polynuclear hydrocarbons give characteristic color reactions when concentrated sulfuric acid and benzal chloride are added. These colors are not very stable. Sawicki substituted trifluoracetic acid for the sulfuric acid and achieved greater stability by the use of chloroform as a solvent. In many instances Sawicki found that it was necessary to add sulfuric acid to obtain a positive test.

A third test is the piperonal chloride test, and Sawicki, Miller and Hauser (Ref I-29) describe a test for polynuclear hydrocarbons using piperonal fluoride. These tests are similar to that using benzal chloride.

At present, no investigators have reported the measurement of polynuclear hydrocarbons from jet engines, but polynuclear hydrocarbons have been found in measurable quantities in the exhaust gases of piston engines.

Aldehydes

Wilson's paper (Ref I-24) contains a review of the determination of aldehydes in air. A fluorometric determination based on reaction with acetylacetone is claimed to detect 0.01 μg. A method claimed to be specific and accurate to 5-10% in the μg range involves reaction with phenylhydrazine and oxygen in an alkaline medium to give a product read by a colorimeter. Rayner and Jephcott describe a method in which Schiff's reagent is used with acetone to increase the color intensity and stability. They claim a sensitivity of five parts per billion (ppb) in 1.5 liters of air and a 72 per cent collection efficiency for an impinger using .005N hydrochloric acid sampling air at 1 CFM.

Another method for measuring aldehydes at the ppb level involves the use of acid-bleached para-rosanaline and dichlorosulfitomercurate complex, and has been used successfully in a mobile laboratory for over four years (Ref 1-29). A red color is developed by oxidation with potassium hexacysuofferate in detector tubes using silica gel impregnated with phenylhydrazine hydrochloride.

The only method presently available which successfully analyzes aldehydes on a continuous, automatic basis is the Technicon Auto Analyzer wet chemical technique. A non-dispersive infrared technique is promising, but is not yet available.

Rounds and Pearsall (Ref 1-30) found that it is sometimes necessary to distinguish between total aldehydes and formaldehyde in a sample. They did this in an attempt to find correlations between the odor and irritant properties of diesel engine exhaust gases. An absorbing agent, phenylhydrazine hydrochloride in solution, was used. This method depends on the formation of an intense magenta color when dilute solutions of formaldehyde hydrazones are treated with potassium ferricyanide solution in the presence of excess hydrochloric acid. The depth of color is proportional to the concentration of formaldehyde present. This method has been found to have the disadvantage that the color produced is not stable. Jacobs (Ref 1-18) altered the preparation of the reagents and changed the order of the addition of the reagents and obtained a stabilized color.

The concentration is determined by light absorption with a photoelectric colorimeter.

The method used by Lozano (Ref I-23) in his study of jet engine exhausts in test cells is the 3-ethyl-2-benzothiazolone hydrazone hydrochloride (MBTH) method. This method is applicable to the determination of total water soluble aldehydes (measured as formaldehyde) in an atmosphere.

Formaldehyde, acrolein and total aliphatic aldehydes have been analyzed by collecting samples from motor vehicles in bubblers for one hour periods (Ref I-22). The chromotropic acid method is used for formaldehyde analysis. The 4-hexylresorcinl method is used for acrolein and the 3-methyl-2-benzothiazolone hydrazone hydrochloride (MBTH) method is used for total aliphatic aldehydes. The absorbtances of the resulting solutions are measured with a spectrometer using 1-inch diameter curettes to insure sensitivity of less than 5 ppb for each analysis.

Peroxyacetyl Nitrate (PAN)

Peroxyacetyl nitrate may be determined by using an Aerograph Hy-Fi III Model 1220-1 Gas Chromatograph with an electron capture detector. A packed column is used for initial separation. Scott anticipates the development of a capillary column in the near future, which will permit analysis for higher homologs such as peroxypropionyl and peroxybutyryl nitrate. It is also hoped that the atmospheric presence of peroxybenzoyl nitrate, which was recently isolated in chamber studies by General Motors Research, can be determined. This compound was reported to be 200 times as powerful an eye irritant as formaldehyde. The Hy-Fi 1220-1 is designed for capillary use and has linear temperature programming. The fact that lower column temperatures are needed with capillary columns than with packed columns should overcome the current problem of decomposition of peroxyacetcl nitrates at room temperatures which are required for separating and eluting the entire series with packed columns.

REFERENCES

1-1. George, R. E. and Burlin, R. M., Air Pollution from Commercial Jet Aircraft in Los Angeles County, Air Pollution Control District, County of Los Angeles, April, 1960.

1-2. Williamson, R. C. and Russell, J. A., "On Line Gas Analysis of Jet Engine Exhaust", SAE paper #670945 presented at the Combined Fuels and Lubricants Powerplant and Transportation Mtgs., Pittsburgh, Pa., October 30-November 3, 1967.

1-3. Reagan, John A., "Applying LIDAR as an Atmospheric Probe", Lasar Focus, June, 1968.

1-4. Barrett, E. W. and Ben-Dov, O., "Application of the LIDAR to Air Pollution Measurements", J. Appl. Meteorol., vol. 6, 1967, pp. 500-515.

1-5. Lieberman, A., "Composition of Exhaust from a Regenerative Turbine System", Air Pollut. Control Assn. J., vol. 18, March, 1968, p. 3.

1-6. Billings, C. E., et al, Open Hearth Stack Gas Cleaning Studies. Semi-Annual Report (SA-16), Harvard Univ. School of Public Health, Boston, Mass., February, 1962.

1-7. Gordon, D. and Dennis, R., "Use of a Single Stage Boundary Layer Diluter in Conjunction with the Royco Particle Counter", paper presented at the Joint Tech. Mtg. of the APCA-AIHA-HPS, Auburn, Mass., May, 1965.

1-8. Gussman, R. A., et al, "Factors in Condensation Nuclei for Measurement of Aerosol Agllomeration", presented at the 7th USAEC Air Cleaning Conference, Brookhaven National Laboratory, New York, October, 1961.

1-9. Fuchs, N. A., et al, "On the Determination of Particle Size Distribution in Polydisperse Aerosols by the Diffusion Method", Brit. J. Appl. Phys., vol. 13, 1962.

1-10. Twomey, S. and Severynse, G. T., "Measurements of Size Distributions of Natural Aerosols", J. Atm. Sciences, vol. 20, 1963.

1-11. Connor, W. D. and Hodkinson, J. R., A Study of the Optical Properties and Visual Effects of Smokestack Plumes, Co-operative Study Project, Edison Elec. Inst. and U. S. Public Health Service, 1963.

1-12. Gruber, C. W. and Schumann, C. E., "Soiling Potential--A New Method for Measuring Smoke Emissions", J. Air Pollut. Control. Assn., vol. 16, 1966, p. 5.

1-13. Shaffernocker, W. M. and Stanforth, C. M., "Smoke Measurement Techniques", presented at the SAE Air Transportation Mtg., New York, N. Y., 1968.

1-14. Ringlemann, I., "Ringlemann's Smoke Chart", U. S. Bureau of Mines Information Circular 8333, 1967.

1-15. Fiorello, S. C., The Navy's Smoke Abatement Program (SAE Paper No. 680345), Society of Automotive Engineers, Air Transportation Meeting, New York, April, 1968.

1-16. Faitani, J. J., Smoke Reduction in Jet Engines Through Burner Design (SAE Paper No. 680348), Society of Automotive Engineers, New York.

1-17. Jacobs, M. B. and Hochheiser, S., Anal. Chem. (AC No.3), vol. 30, 1958, p. 426.

1-18. Jacobs, M. B., "The Chemical Analysis of Air Pollutants", Interscience Publ., New York, London, 1960.

1-19. Saltzman, B. E., "Selected Methods for the Measurement of Air Pollutants", Public Health Service Publ. No. 999-AP-11, 1965.

1-20. Ganz, G. and Kuznetsou, I., "Automatic Gas Analyzer for Oxides of Nitrogen", Ind. Lab. (IL No. 1), vol. 33, 1967, pp. 126-128.

1-21. Smith, D., et al, "Oxides of Nitrogen from Gas Turbines", Air Pollut. Control Assn. J., vol. 18, 1968, p. 1.

1-22. Scott Research Labs., Inc., Private Communication, Perkasie, Penn., July, 1968.

1-23. Lozano, E. R., et al, Air Pollut. Control J., vol. 18, 1968, p. 392.

1-24. Wilson, H. N. and Duff, G. M. S., "Industrial Gas Analysis. A Literature Review", The Analyst, vol. 92, December, 1967, p. 1101.

1-25. McEwen, D. J., "Automobile Exhaust Hydrocarbon Analysis by Gas Chromatography", Anal. Chem., vol. 38, 1966, pp. 1047-1053.

1-26. Korth, M. W. and Rose, A. H., Jr., "Emission from a Gas Turbine Automobile", SAE paper #680402, presented at the Midyear Mtg. of Soc. of Automotive Engineers, Detroit, Michigan, May 20-24, 1968.

1-27. Klosterman, D. L. and Sigsby, J. E., Jr., "Application of Subtractive Techniques to the Analysis of Automotive Exhaust", J. Environ. Sci. & Tech. (JES&T No. 4), vol. 1, April, 1967, p. 309.

1-28. Sawicki, E. and Miller, R. R., Detection of Puriene, Benzo(a)pyrene and Other Polynuclear Hydrocarbons, Sanitary Engineering Center, U. S. Public Health Service, Cincinnati, 1957a.

I-29. Sawicki, E., et al, Depiction of Polynuclear Hydrocarbons and Phenols with Benzal and Piperonal Fluorides, Sanitary Engineering Center, U. S. Public Health Service, Cincinnati, 1957b.

I-30. Rounds, F. G. and Pearsall, H. W., "Diesel Exhaust Odor", SAE National Diesel Engine Mtg., Chicago, 1966.

APPENDIX II

THE ORIGIN AND MEASUREMENT OF ODOR IN AIRCRAFT ENGINE EXHAUST EMISSIONS

Odor Mechanisms

The literature on the measurement, control, and theory of odor notes repeatedly that a compound must be volatile to be odorous. This assumption forms part of the basis of current ideas on olfaction, which have recently been reviewed by Roderick (Ref II-1). It is also sometimes inferred that the transfer of odorous material from a solid or liquid source to a human sensor always occurs by vaporization of the source material, and by subsequent diffusion or convection of the gaseous odorant until it reaches the nasal cavity of the subject. There is evidence, however, that this picture is incomplete, and that particulate matter can play a role in the transfer and/or perception of odors by humans. Since the production of particulate matter is a significant occurrence in aircraft engine exhaust, it will be helpful first to consider what these possible effects might be.

Odors Possibly Due to Particles in Aircraft Engine Exhaust

No study has ever rigorously defined the upper limit of particle size for airborne odorous matter. Particles up to about 0.8 or 1 nm in diameter are considered to be molecules that can exist in equilibrium with a solid or liquid phase from which they escape by vaporization. The vapor pressure decreases as the molecular weight increases, and particles above about 1nm do not generally exist in any significant concentration in equilibrium with a bulk phase; hence we do not consider them to be "vapors".

Nonetheless, it is possible that odorant properties do not disappear when particle sizes exceed those of vapor molecules. Our knowledge about particles in the size range of 1-5 nm (up to about the size of small viruses) is relatively meager, and we do not know whether or not they can be odorous, nor what the effect of an electrical charge on their odorous properties might be. Larger particles may also be intrinsically odorous, although their more significant role may be to contribute to odor by absorbing and desorbing odorous gases and vapors.

Odors Possibly Due to Desorption of Gases from Particles

Goetz (Ref 11-2) has treated the kinetics of the interaction between free gas molecules and the surface of airborne particles. His theoretical considerations were directed to the question of transfer of toxicants by particles, but are also applicable to odors. If we assume that a given aerosol is intrinsically odorless, then it can act as an odor intensifier if it has a sorptive capacity for the odorant large enough to produce an accumulation on the particle surface, but smaller than the affinity of the odorant for the nasal receptor. In such case, the aerosol particles will concentrate molecular odorous matter on their surfaces, but the particles will not retain the odorous matter when they reach the olfactory receptors. Instead, the odorous matter will be transferred to the receptor sites in a higher concentration than would exist in the absence of the aerosol. The resulting effect will be synergistic. If, on the other hand, the affinity of the molecules for the particles exceeds that for the receptor surface, then the transfer of odorous matter to be nasal receptors is impeded and an attenuation of the odor will occur.

Odors Possibly due to Volatile Particles

Liquid or even solid aerosols may be sufficiently volatile so that when they enter the nasal cavity, their vaporization produces enough gaseous material to be detected by smell. Such aerosols may be relatively pure substances, like particles of camphor, or they may be mixtures which release their more volatile components. The odor intensity associated with volatile aerosols will, of course, depend on the prevailing temperature and on the length of time they are dispersed in air. In a cold atmosphere, the temperature rise accompanying inhalation will accelerate the production of gaseous odorant.

The idea that odors are associated with particles is supported by observations that filtration of particles from odorous air stream can reduce the odor level. Rossano and Ott (Ref II-3) showed that the removal of particulate matter from diesel exhaust by thermal precipitation effected a marked reduction in odor intensity. Thermal precipitation was selected for the good reason that this method provides minimal contact between the collected particles and the gaseous components of the diesel exhaust stream. In this way, the effects that could be produced by a filter bed, such as removal of odorous vapors by absorption in the filter cake, were eliminated. Thermal precipitation does not remove gaseous or vaporous material, and the observed odor reduction must therefore, have resulted directly from the removal of particulate matter. The particles collected by Rossano and Ott were aggregates of spherical balls about 0.04-0.05 micrometers (400-500Å) in diameter. It is possible that any one or a combination of the three possible aerosol odor effects described above could have been responsible for the observed results. Particulate matter from diesel exhaust collected on glass fiber filters by Linnell and Scott (Ref II-4) yielded a heavy "diesel" odor. Analysis of the particulate matter showed that it contained no acrolein or formaldehyde, although it did release NO_2 on being heated to 100°C. The authors conclude that "no appreciable gas phase concentration changes for acrolein or formaldehyde will result from particulate removal". Other more or less casual observations on the role of particulate matter in community odor nuisance problems appear occasionally in the literature.

The association of particulate matter with outdoor odors is also implied by the fact that predictions of odor intensities based on gas phase dispersion of an odor source are often in gross error (Ref II-5). These discrepancies between calculated dilutions and odor measurements may therefore be caused by one or more of the possible particle effects noted above.

Odor Measurement

General

"Odor measurement" may imply the chemical analysis of odorous substances, or the sensory evaluation of odor stimuli, or a combination of both methods of appraisal, with some establishment of relationships between the two sets of results (Ref II-6). In the case of exhaust from combustion of hydrocarbon fuels, chemical analysis alone, even if it were to be qualitatively and quantitatively complete, would be uninformative with regard to odor, because identification of components does not establish their relevance to the odor of the mixture. The eventual determination of odor relevances of the components of aircraft engine exhaust is a valid objective, however, because such information would make it possible to predict sensory effects from chemical analysis.

Discriminatory sensory evaluations of odors are concerned with odor intensity or odor quality; affective evaluations measure odor acceptability (Ref II-7). The development of odor acceptability ratings (so-called "hedonic scaling") has been applied mainly to flavors of foods and beverages (Refs II-8 and II-9), and only very little to odor problems associated with air pollution (Ref II-10). The translation of a hedonic, or like-dislike scale, to an action scale, that rates affective properties of odors in terms of the anticipated behavioral response of people, has been applied only to food acceptance (Ref II-11). The relevant action response for odors associated with foods is eat-not eat, or buy-not buy. For odors associated with air pollution, the action responses may well be much more complex; in any event, no such scaling has yet been reported. Therefore the only sensory evaluations that will be considered in this report are discriminatory ones--odor intensity and odor quality.

Sampling for Odor Measurement

General

When odors are perceived at some distance from the aircraft engine exhaust such that the odor intensities are tolerable, at locations such as terminal buildings, aircraft passenger gate areas, and the community areas adjacent to airfields, sensory odor judgments are best made by direct exposure of the judges to the odorous atmosphere without prior sampling. Such atmospheres usually vary in odor intensity from time to time, depending on variations in number and proximity of aircraft, and in wind velocity, direction, and turbulence. Therefore, an adequate sampling program would be very costly. Furthermore, outdoor ambient odor samples are difficult to preserve in containers, because even a small amount of absorption on the walls detracts seriously from the samples. The fact that odor levels under such conditions vary in intensity from time to time, however, constitutes an advantage for direct sniffing by the observers, because the variations usually provide adequate opportunity for recovery from olfactory fatigue between judgments. Each judge is, in effect, making a measurement with each sniff, without being fatigued during the times that he is not detecting odor. An observer may also move about from place to place in an area of suspected odor, either by foot or automobile, and spend most of his time making judgments at locations where the odor levels are highest.

There are some instances, however, in which it is advantageous or necessary to collect a sample of odorant before presenting it for sensory measurements. The most significant instance of this type will be the direct sampling of engine exhaust for sensory odor evaluation, where cooling and dilution will necessarily precede exposure of judges. Other instances may involve the necessity of moving an odor sample to a special location for testing, away from aircraft engine exhaust backgrounds. When chemical analysis of odorants is to be carried out, sampling with concentration may be necessary.

Grab Sampling

A grab sample places a volume of odorant at barometric pressure into a container from which it can subsequently be presented to judges for evaluation. Grab sampling of odorants is subject to some severe limitations:

(a) If the odorant is close enough to the engine so that it is hot, condensation may occur on cooling. The condensate will probably contain odorous material at the expense of the concentration in the gas phase. (b) During the time between collection and evaluation, odorous material may be sorbed on the walls of the container or on particulate matter in the air sample. (c) Chemical interactions among the exhaust components may alter the odorant.

Containers for grab sampling should therefore be inert to the odorant material, and should have a large volume-to-surface ratio. If the odorant being sampled is not at ambient temperature, the investigator must assure himself that condensation will not occur on cooling.

Grab sampling is carried out by allowing the air to fill an evacuated or collapsed container, or to displace a fluid from a container. Suitable materials of construction may include stainless steel, glass, or plastics such as Mylar, Teflon, and Saran (Refs 11-12 and 11-13). Any container, however, together with its auxiliary tubing and equipment like air moving devices, must be tested for suitability for the specific engine exhaust odorant in question, especially with regard to extraneous background odor of the airport area, and to depletion of sample by adsorption or absosption effects.

When the grab sample is to be evaluated, it must be expelled from the container into the space near the judge's nose. This expulsion may be effected by displacement of the sample with another fluid, or by collapsing the container. The following example is given as an illustration of grab sampling.

Example 1. A sampling probe of 1" diameter Teflon tubing is mounted so that its inlet end is close to the upstream side of a central activated carbon purification unit in an aircraft passenger terminal building. A blower of suitable capacity draws air through the probe and discharges it into a collapsed Mylar bag of about 2 ft.^{3} capacity. The sampling procedure is repeated on the downstream side of the carbon unit at different times during the life of the carbon bed. The samples are then removed to a suitable test room where a panel of judges can appraise them by sensory measurements such as those elaborated in subsequent sections.

Sampling with Dilution

Dilution procedures for sampling aircraft engine exhaust can reduce concentrations and temperatures to levels suitable for human exposure without permitting condensation of the odorant material. The dilution ratio must be specified and can be determined on the basis of either pressure or volume. The material of choice for dilution of a sample of aircraft engine exhaust is stainless steel. A suitable device is a 1000 cu. in. stainless steel tank fitted with a flow control inlet valve, a constant differential type flow controller and two additional valves, one between the flow controller and the tank, and the other at the opposite end of the tank (Ref 11-14). Before use in sampling, the tank is evacuated, and the inlet valve is adjusted to the desired flow rate, as indicated on a flowmeter. Once the adjustment is made, the handle is removed from the inlet valve and its stem is sealed with wax so as to insure against accidental tampering; the tank is then reevacuated and the two seal valves are closed. For sampling, it is necessary to open only the seal valve between the flow controller and the tank and to record the time during which the odorant is being sampled. The total volume of sample will be equal to the time of sampling multiplied by the flow rate through the inlet valve. The flow controller assures that this rate will be constant over the sampling period if the tank is not filled beyond about 75% of its capacity. As an alternate method, the flow control system is omitted and the end opposite the sampling probe is fitted with a vacuum gage; the partial pressure of the odorant is then the difference between the vacuum readings before and after sampling. The method is further illustrated by the following example.

Example 2. For direct sampling of jet exhaust odorant, a stainless steel tank fitted with a length of stainless steel tube probe is evacuated to a pressure of 50 torr. The steel probe is inserted in the exhaust and a sample is drawn into the tank until the pressure reaches 60 torr. At this point the temperature of the gas mixture in the tank is 28°C. The tank is now pressurized with odor-free air to 3.00 atmosphere (2.28×10^3 torr). The final temperature is 22°C.

$$\text{The dilution ratio then is} \quad \frac{2.28 \times 10^3 \text{ torr}}{(60-50) \text{ torr } \frac{(273 + 22)}{(273 + 28)}} = 233$$

The diluted sample in the tank is then removed to a test room where judges can draw samples for sniffing simply by opening the valve. A sequence of samples taken from the engine exhaust under different conditions can be used for comparative tests.

Sampling with Concentration

If it becomes necessary to correlate sensory odor measurements with chemical analysis at places where people are directly exposed to aircraft engine exhaust odors, a grab sample may be too dilute for adequate chemical characterization. For example, a grab sample taken near a passenger gate area would probably show only a generalized hydrocarbon response when examined by infrared spectrometry. This information would be inadequate even for purposes of comparing infrared profiles under different conditions. Other analytical responses are likely to be even less informative. Analytical characterization of odorants can be highly improved by concentrating them during sampling. Freeze-out, adsorptive, and absorptive sampling have all been used.

In freeze-out sampling (Refs 11-15 and 11-16), the odorant air stream is passed through a cold trap that freezes and holds the odorous substances but does not retain the major non-odorous components. Unfortunately, the trap retains water. The coldest permissible refrigerant is usually liquid air. Liquid nitrogen may condense oxygen in the trap, thus creating a hazard of pressurization when the trap is sealed and the refrigerant is removed. The trap should accommodate the relatively large quantity of ice that is collected, and a filter for the aerosol matter that is usually formed. The designs of Shepherd (Ref 11-16) and Turk (Ref 11-17) both provide these features. Freeze-out sampling for odorants is advantageous because interactions among the concentrated components are minimized at low temperatures. A serious disadvantage is the icing of practically all the water in the air being sampled. Of course, a desiccant can be placed before the cold trap, but the desiccant may adsorb or absorb odorous matter and invalidate the sampling (Ref 11-18).

In adsorptive sampling (Refs 11-19, 11-20 and 11-21), the odorant air stream is passed through a bed of activated carbon, silica gel, or (much less frequently) some other adsorbent to concentrate the odorous material. Activated carbon is advantageous because it adsorbs organic matter in preference to water, and excessive aqueous dilution of the collected odorant therefore does not occur (Ref 11-22). Activated carbon is so retentive to most odorous matter, however, that recovery may be difficult. Desorption of the odorant from the carbon in vacuo into a cold trap is effective, but may involve isomerization or other chemical changes (Refs 11-17 and 11-23). Solvent extraction of the odorant is a less drastic method but may yield much less recovery (Ref 11-24). When the degree of concentration needed is small enough, and the ambient air is dry enough so that water collection is not a serious problem, silica gel may be used in place of carbon, with the advantage that milder conditions for odorant recovery can be used (Refs 11-25, 11-26 and 11-27).

Absorptive sampling is sometimes advantageous when one desires to concentrate and hold an odor sample easily and with minimum manipulation of equipment. If the concentration factor need not be known precisely, it may be convenient to use an odorless solvent, like mineral oil, carried on a relatively inert material like absorbent cotton. A wad of such absorbent material may be suspended in an odorous space and subsequently removed for odor evaluation.

Odorants may be collected by equilibration in a stationary liquid phase, from which they can be subsequently released (for example, into a gas chromatograph) by heating (Ref 11-28). The most recently described system of this type uses a fluidized bed of Teflon powder coated with Apiezon L stationary phase (Ref 11-29).

Odor Intensity

The intensity of an odor is the magnitude of the stimulus produced when a person is exposed to an odorant. In measurements of odors involved in air pollution, the usual practice is to use threshold measurements as an index of odor intensity, with the assumption that more intense odors have lower threshold values. In fact, the one reported jet engine emission odor study (Ref 80) utilized odor dilution threshold measurements. Other very recent reports are also concerned with threshold methods (Refs II-30 and II-31). It is therefore important to consider what information on odor intensity can be obtained from threshold measurements.

The odor threshold is the minimum concentration at which an odorous substance can be distinguished from odor-free air ("detection threshold") or at which its quality can be recognized ("recognition threshold", or "minimum identifiable odor", MIO). The latter is the higher value. Odor threshold levels depend on the nature of the substance and on the sensitivity of the judge. The "50% threshold" is the concentration at which the odor can be detected (or recognized) by 50% of the population.

Threshold data, strictly speaking, can be used to predict the conditions under which a given substance will be odorous or odorless. Such predictions provide a basis for calculating (a) the degree of dilution, by ventilation or outdoor dispersal, that is needed to deodorize a given odor source, (b) the proportion of odorant that must be removed from a space, by methods such as activated carbon adsorption, to effect deodorization, (c) the amount of a substance that must be injected into a space to odorize it, or (d) the volume of air that can be odorized by a given amount of substance. Threshold concentrations are not, however, direct measures of odor intensity at supra-threshold levels.

The threshold values reported in the literature scatter over wide ranges, for example 3.2×10^{-4} p.p.m. to 10 p.p.m. for pyridine. Such variances have been assumed to result from impurities, differences in mode of presentation of odorants, differences in subjects (Ref 11-31), calibration errors (Ref 11-32), and the like. More serious is the supposition that the "threshold value" is not a specific property of an odorant substance at all, to be approached more and more closely as our techniques of sensory evaluation grow more precise (Ref 134). Instead, it is a property that depends heavily on the motivations and expectations of the observers, and that can be manipulated by rewards and punishments. These findings lead to the conclusion that threshold values will always be a shaky index on which to base supra-threshold measurements of odor intensity.

The threshold level, C_t, is often measured by quantitative dilution of a given volume, V, of odorant of known concentration, C. Then $C = W/V$, and $C_t = W/V_t$, where W is the quantity of odorant and V_t is the volume of sample after it is diluted to threshold level.

Dividing and solving for C_t,

$$C_t = CV/V_t$$

The same procedure can be applied to characterize an odorant or odor source of unknown concentration. The then threshold dilution ratio, $V_t/V = C/C_t$. This ratio, also called the threshold odor number, or the odor pervasiveness (Ref 11-33), can be used as a basis for the same calculations as those previously cited for the odor threshold concentration.

A related unit, called the "odor unit", is defined as one cubic foot of air at the odor threshold (Ref II-34). A cubic foot of odorant that must be diluted to n cubic feet to reach the odor threshold level is said to contain n odor units. The odor concentration of an odorant is then expressed in terms of "odor units per cubic foot". This nomenclature is unfortunate in that the meaning of "concentration" is foreign to chemical usage, but it will be recognized that it is identical with the threshold dilution ratio, with volumes being expressed in cubic feet.

Dilution methods have been described by several workers (Refs II-30, II-35, II-36, II-37 and II-38) and the general principles were explained earlier. In the light of the gross variances in odor threshold data, it must be assumed that nominal dilution factors, calculated from ratios of volumes or flow rates in a dilution system, are unreliable. An absolute method for establishing the reliability of a dilution method involves reconcentrating the odorant and verifying the reestablishment of the original concentration. The maximum error in such a procedure can be calculated on the following basis: Assume that an initial concentration of odorant, C_i, is sufficiently high so that it can be determined accurately by a reliable method of analysis. The odorant is then diluted by a factor, F_d, that is nominally determined by volume or flow ratios in the system, to a lower concentration C_d. Now, using some method such as freeze-out trapping, the diluted odorant is reconcentrated by a factor, F_r, to recover a high concentration, C_r, which, like C_i, can be determined accurately. Now, the value for the concentration of the diluted odorant that is calculated without a confirming analysis from the applied dilution factor is

$$C_{d(calc.)} = C_i F_d$$

The reconcentrated value is

$$C_r = C_d F_r, \text{ and } C_d = C_r / F_r$$

Now, the error in measuring C_d is

$$\text{Error (fractional)} = \frac{C_{d(calc.)} - C_d}{C_{d(calc.)}} = \frac{C_i F_d - C_r / F_r}{C_i F_d}$$

$$= 1 - \frac{C_r}{C_i F_d F_r}$$

If $F_d = 1/F_r$, that is, if the original concentration is nominally restored after dilution, the Error $= 1 - \frac{C_r}{C_i}$.

Note that in this calculation it is assumed that recovery of the diluted odorant is complete and that all the error lies in the dilution procedure. If some loss occurring during reconcentration is thus erroneously ascribed to the dilution, then the calculated dilution error is too high. There is no way to resolve this question except to state that the calculated error is a maximum value, and that the real error therefore cannot be any greater than that obtained by this procedure. Turk, Edmonds, and Mark (Ref II-32) have shown that a tracer gas like SF_6 can be used to explore inherent errors in a gas dilution system.

In any dilution method, important consideration must be given to the diluent. When dilutions are carried out in the field, the dilution air is ambient air purified by passage through activated carbon. The "Scentometer" (Barnebey-Cheney Co., Columbus, Ohio) is a simple, portable device of this kind that uses a carbon bed to supply dilution air. However, it cannot be assumed, without further check, that dilution air prepared in different ways will have equal effects on determined threshold values.

Odor intensity can be measured on a scale (called a psychophysical scale) whose reference points are fixed in some physical way. The most conventional physical standards are odorant substances of known and reproducible composition and concentration. Because odor, like other sensations, is a logarithmic or power function of the stimulus (Ref II-39), it is appropriate for the concentrations of the reference odor standards to be distributed along some exponential scale; a convenient scale is based on exponents of 2. The procedure is illustrated by the following example.

Example 3. The intensity of a series of odors caused by raw jet fuel is to be measured. The reference standards are the vapor phases in equilibrium with an exponential concentration series of octyl benzene solution in odorless mineral oil at 25°C. The solutions are:

	Dilution #	Concentration of octyle benzene in mineral oil	
Strong	1	1	(100%)
	2	1/2	(50%)
	3	1/4	(25%)
Moderate	4	1/8	(12.5%)
	5	1/16	(6.25%)
	6	1/32	(3.13%)
Slight	7	1/64	(1.56%)
	8	1/128	(0.78%)
	9	1/256	(0.39%)

About 25-30 ml. (1 fl oz) of each solution may be placed in a 4 oz plastic squeeze bottle. A judge sniffs the odor standard when he squeezes the bottle to expel about half (50 ml) of the vapor phase in equilibrium with any given solution. Instructions are given to the judges as follows: "The samples lined up in front of you all contain solutions of a fuel odor in mineral oil. They differ from each other in odor strength, the most intense odor is on the left, and the intensity gradually gets less from sample to sample towards the right. You are to judge the jet fuel odor intensity of the unknown sample by picking the standard solution that matches its intensity most closely."

The example above uses n-octylbenzene because it is found that this is a stable substance which provides a good reference for this odor measurement (Ref 11-40). It is available commercially, but must be analyzed (gas chromatography) and, if necessary, redistilled to remove impurities.

It has been suggested (Ref 11-41) that n-butanol may be used as an odor reference standard for all airborne odors, even though they differ markedly from it in quality, but we do not know to what extent such divergence is disadvantageous.

Judges may make subjective estimates of magnitude between points that are represented by reference standards. It is also possible for a judge to estimate intensity ratios that are based on only one reference point. Thus, a judge may estimate that a given phenolic odor is five times as strong as that of a standard phenol odorant. Measurements set up in this way are called ratio scales.

Some odor intensity scales are not anchored in specific reference standards at all, but instead are defined by descriptions like "slight", "moderate", "strong", and "extreme". Such adjectives are actually implied reference standards, because an odor judge, even without instructions, will refer to his experience. Thus, for example, a fragrant odor of "moderate" intensity may be taken to mean the typical odor level in a level in a florist shop. Such scaling can be grossly imprecise.

Odor Quality

The quality of an odor is its character described in terms of resemblance to some other odor. Descriptions of quality include words like "burnt", "oily", "musky", and "phenolic". If a general description of odor qualities could be set up, it would be possible to describe any odor in terms of a number of primary odor standards (Refs II-42, II-43, II-44 and II-45). Taking the Crocker-Henderson system as an example of this sort, odors are classified according to four primary qualities: fragrant, acidic, burnt, and caprylic (goaty or rancid). Each quality is also rated on an odor intensity scale from 0 (none) to 8 (strongest). Thus, acetic acid is described by the number 3803, which implies that the odor is moderately fragrant, highly acidic, not burnt, and mildly caprylic. Systems of this type, though they date from 1895 or earlier and are described in standard psychological texts have not become useful methods of odor measurement in air pollution problems. The reason is that no conceptual system has yet been devised which accurately predicts odor quality from the chemical composition of the odorant, especially from such complex mixtures as outdoor pollutants, or vice versa, or explains the detailed mechanism of odor perception. As a result, the odor quality classifications are largely empirical and are usually compromises between high specificity, which requires many reference qualities, and convenience, which implies that the reference qualities should be few and universally recognized.

An empirical approach that does not entail any assumptions concerning primary odor types can be realized by using specific odor quality descriptors that are represented by odor quality reference standards. In this method, the group of odors to be judged is defined in terms of a few (usually 3 to 8) qualities that seem reasonable in the light of subjective associations and chemical analysis. The selections are made by people who are familiar both with the odors in question and with the analytical findings, even though the latter may be incomplete. Then an odor quality reference standard is made up to represent each quality description. The chemicals used in a reference standard represent the best choice available on the basis of odor, stability, lack of toxicity, and correspondence with constituents that are known or suspected to exist in the odorant. Each reference standard may then be expanded into a dilution scale using a suitable odorless diluent (as mentioned above). For convenience, and in order not to overload the judges' capacity for yielding informative responses, the number of points on the dilution scale should correspond to the following relationship: No. of quality stds. x No. of intensity stds. per quality = 10 to 32. Then an odor to be appraised may be described in terms of intensities of the various qualities by proper matching with the reference standards, as in the Crocker-Henderson system. Such a description is called a quality-intensity profile. This procedure is illustrated by the following example:

Example 4. Diesel exhaust is to be appraised in terms of its quality-intensity profile (Ref II-40). It is found that the odor can be characterized in terms of four descriptors: burnt/smoky, oily, pungent/acid, and aldehydic/aromatic. The odor quality reference standards are made up of the following components: (burnt), oil of cade (Juniper tar), guaiacol, carvacrol, and acetylenedi-carboxylic acid; (oily), n-octylbenzene; (pungent/acid), crotonic acid and propiolic acid; (aromatic/aldehyde), a mixture of aromatic hydrocarbons and aromatic and aliphatic aldehydes. Each reference standard is diluted in mineral oil, with benzyl benzoate added if necessary for solubilization, to four different concentrations representing different levels of intensity. The resulting kit of sixteen reference standards is used as a basis for quality-intensity profiling of diesel exhaust odors.

There have been several other recent approaches to the problem of characterizing odor quality. One is that of Woskow (Ref II-46) who has shown that estimates of similarities among various odors can be used to locate the odors in a psychological "space", such that the closeness between any two odors in the "space" is a good relative measure of the degree of similarity expressed by observers. Furthermore, he finds that a good representation can be obtained with as few as three dimensions, one of which is pleasantness, and the other two are rather difficult to define. The method is structurally capable of describing any odor by specifying its position in the space, but it has not yet been shown whether this objective can be realized.

Another method is that of Harper (Ref II-47), who has classified odor qualities by the responses of experienced and inexperienced subjects who refer to a list of 44 suggested quality descriptions. The result is a glossary in which each odorant is characterized in terms of the various descriptions elicited in these responses. The method has been reported only for pure odorants, not for mixtures, and is unlikely to be usable, in its present form, for informative quality descriptions of aircraft engine exhaust odors.

Selection and Training of Odor Judges

Although many procedures for the statistical analysis of sensory measurements have appeared in the literature (Ref II-8), the simplest and most satisfactory for selection of odor judges for discrimination panels are those of Wittes and Turk which have been used in various diesel studies and which are recommended for studies of aircraft engine exhaust odors. If only odor intensities are to be measured in a given study, the test for quality may be omitted. It is particularly important, in odor studies involving aircraft, to rule out potential panel members whose responses may be impaired by the extra distractions that may be encountered in airfield areas.

Screening tests should be conducted at low levels of statistical confidence (~25%), with one of two objectives: (a) If a large panel is to be used (over 15), the procedure should rapidly accept most of the able candidates while rejecting the very obviously unsuitable ones. (b) If a small panel is to be used, the screening procedure should rapidly eliminate most of the unsuitable candidates, even though some potentially able ones will thus be lost.

The first step in the training procedure should be the repetition of the screening tests, with group discussion and evaluation of results, until a high performance plateau is reached (1-2 days). The subsequent steps should be patterned very closely after the actual experimental designs to be followed in the tests. If reference standards are to be used, the panel members should learn them. If these are to be conducted in airport areas, the panel members should be exposed to field conditions. During this period, additional screening should take place, with elimination of unsuitable judges.

Correlations between Instrumental Analysis and Sensory Properties of Odors

Odorants, like other substances, are amenable to chemical analysis. Hydrocarbon fuels are complex substances because they contain many components. Combustion products of hydrocarbon fuels are much more complex because of the additional components introduced by cracking and by partial oxidation processes. Since the specific chemical and physical determinants of odor are not yet known, a chemical analysis of itself, no matter how complete, is not a measurement of odor. To correlate the chemical with the sensory properties of an odorant, it is necessary to assign odor intensity and quality attributes to the various components that the analyst has identified, and possibly to consider interaction effects. Very few complex odorous substances have been carefully investigated in this way. Those for which satisfactory instrumental-sensory relations have been worked out have been food odors and essences, such as those of apple, cucumber, and banana (Ref II-6). There have been attempts to accomplish similar results with diesel exhaust odors (Refs II-48 and II-49), and work in this area is still in progress in several laboratories, but results have not approached the point where analytical information can predict sensory properties. It is not likely that work with aircraft engine exhausts would be any easier.

Dravnieks and Krotoszynski (Ref II-29) have recently reported on procedures for establishing "odor relevance" of specific components of an odorous air sample, which involves sensory evaluation of components that correspond to individual peaks from a gas chromatographic trace. Procedures of this kind have been used before, especially in the various food odor studies cited above. However, the possibility that some odor-relevant components of hydrocarbon combustion are labile in air (for example, carbon suboxide), and could be destroyed during examination, adds to the difficulty of the problem.

REFERENCES

11-1. Roderick, W. R., J. Chem. Educ. (JCE No. 10), vol. 43, October, 1966, p. 510.

11-2. Goetz, A., Int'l. J. Air & Water Pollution, vol. 4, 1961, p. 168.

11-3. Rossano, A. T., Jr. and Ott, R. R., "The Relationship between Odor and Particulate Matter in Diesel Exhaust," presented at the Annual Meeting Pacific Northwest Internat'l. Section of the Air Pollution Control Assoc., Portland, Ore., November 5-6, 1964.

11-4. Linnell, R. H. and Scott, W. E., "Diesel Exhaust Composition and Odor Studies", Air Pollut. Control Assoc. J. (APCA No. 11), vol. 12, November, 1962, p. 10.

11-5 Wohlers, H. C., "Odor Intensity and Odor Travel from Industrial Sources", Int'l. J. Air Water Pollut., vol. 7, 1963, p. 71.

11-6. American Society for Testing and Materials, Correlation of Subjective-Objective Methods in the Study of Odors and Taste, STP-440, June, 1968a.

11-7. Schutz, H. G., "Recent Advances in Odor", Annals N. Y. Acad. Science (AN.Y.AS, Art. 2), vol 116, 1964, p. 517.

11-8. A. D. Little, Inc., Flavor Research and Food Acceptance, Reinhold Publ. Corp., New York, 1958.

11-9. American Society for Testing and Materials, Manual on Sensory Testing Methods, STP-434, June, 1968b.

11-10. Medalia, N. Z. and Finker, A. L., "Community Perception of Air Quality: An Opinion Survey in Clarkston, Washington", Public Health Service Publ. No. 999, AP-10, 1965.

11-11. Schutz, H. G., J. Food Sci., vol. 30, 1965, p. 365.

11-12. Clemons, C. A. and Altshuller, A. P., J. Air Pollut. Control Assn., vol. 14, 1964, p. 407.

11-13. Connor, W. D. and Nader, J. S., Am. Ind. Hygiene Assn. J., vol. 25, 1964, p. 291.

11-14. Collins, G. F., et al, Air Pollut. Control Assn. J., vol. 15, 1965, p. 109.

11-15. American Society for Testing and Materials, Recommended Practice for Sampling Atmospheres for Analysis of Gases and Vapors, D-1605-60, 1960.

11-16. Shepherd, M., et al, J. Anal. Chem., vol. 23, 1951, p. 1431.

11-17. Turk, A., et al, Anal. Chem., vol. 34, 1962, p. 561.

11-18. McKee, H. C., et al, Paper presented at 136th Nat'l. Mtg., Am. Chem. Soc., Atlantic City, New Jersey, September, 1959.

11-19. Chiantella, A. J., et al, Am. Ind. Hygiene Assn. J., vol. 27, 1966, p. 186.

11-20. Turk, A., et al, "Determination of Gaseous Air Pollution by Carbon Adsorption", Am. Ind. Hygiene Assn. Quart., vol. 13, 1952, p. 23.

11-21. Turk, A. and Mehlman, S., "Correlations Between Instrumental and Sensory Characterizations of Atmospheric Odors. Correlation of Subjective-Objective Methods in the Study of Odors and Taste", Amer. Society for Testing and Materials (ASTM, STP-440), 1968a, p. 27.

11-22. Turk, A. and Van Doren, A., Agr. Food Chem., vol. 1, 1953, p. 145.

11-23. Turk, A., et al, Air Pollut. Control J., vol. 16, 1966, p. 383.

11-24. Brooman, D. L. and Edgerly, E., J. Air Pollut. Control Assn., vol. 16, 1966, p. 25.

11-25. Adams, D. F., et al, TAPPI, vol. 43, 1960, p. 602.

11-26. Altshuller, A. P., et al, Am. Ind. Hygiene Assoc. J., vol. 23, 1962, p. 164.

11-27. Campbell, E. E. and Ide, H. M., Am. Ind. Hygiene Assn. J., vol. 27, 1966, p. 323.

11-28. Dravnieks, A. and Krotoszynski, B. K., J. Gas Chromatography, vol. 4, 1966, p. 367.

11-29. Dravnieks, A. and Krotoszynski, B. K., J. Gas Chromatography, vol. 6, 1968, p. 144.

11-30. Hemeon, W. C. L., J. Air Pollut. Control Assn., vol. 18, 1968, p. 166.

11-31. Leonardos, G., et al, Paper 68-13, Air Pollut. Control Assn. 61 Mtg., June, 1968.

11-32. Turk, A., et al, Environmental Sci. Tech., 1968b, p. 44.

11-33. Turk, A., "Odor Measurement and Control", Chapter 13 in Air Pollution Abatement Manual, Manufacturing Chemists' Assn., Washington, D. C., 1960.

11-34. American Society for Testing and Materials, *Method of Measurement of Odor in Atmosphere (Dilution Method)*, D-1391-57, 1962.

11-35. American Society for Testing and Materials, *Standards on Methods of Atmospheric Sampling and Analysis*, 2nd ed., 1962, pp. 40-43.

11-36. Gordon, D. and Dennis, R., "Use of a Single Stage Boundary Layer Diluter in Conjunction with the Royco Particle Counter", paper presented at the Joint Tech. Mtg. of the APCA-AIHA-HPS, Auburn, Mass., May, 1965.

11-37. Mateson, J. F., "Olfactometry: Its Techniques and Apparatus", *Air Pollut. Control Assn. J.*, vol. 5, 1955, p. 167.

11-38. Nader, John S., "An Odor Evaluation Apparatus for Field and Laboratory Use", *Am. Ind. Hygiene Assn. J.*, vol. 19, 1958, p. 1.

11-39. Stevens, S. S., *Psychol. Rev.*, vol. 64, 1957, p. 153.

11-40. Turk, A., *Selection and Training of Judges for Sensory Evaluation of the Intensity and Character of Diesel Exhaust Odors* (PHS Publ. No. 999-AP-32), 1967.

11-41. Krotoszynski, B. K. and Dravnieks, A., Paper 68-17 in Air Pollut. Control Assn. 61st mtg., June, 1968.

11-42. Amoore, J. E., *Ann. N. Y. Acad. Sci.* (Art. 2), vol. 116, 1964, p. 457.

11-43. Crocker, E. C. and Henderson, L. F., "Analysis and Classification of Odors", *Amer. Perfumer*, vol. 22, 1927, pp. 325-356.

11-44. Foster, D., "A New Method of Predicting the Qualities of Flavor Mixtures", *Instit. of Food Technologists*, January, 1952.

11-45. Henning, H., *Der Geruch*, Leipzig, 2nd ed., 1924.

11-46. Woskow, M. H., "Multidimensional Scaling of Odors", *In Theories of Odors and Odor Measurement*, Robert College Research Center, Istanbul, Turkey, 1968, p. 147.

11-47. Harper, R., et al, *A Glossary of Odor Stimuli and Their Qualities*, Perfumery & Essential Oil Record, London, 1968.

11-48. Holtz, J. C., et al, U. S. Bureau of Mines, R. I. 3508, May, 1940.

11-49. Reckner, L., *Diesel Exhaust Composition, Odor and Eye Irritation*, Scott Res. Lab., U. S. Public Health Service, Contract PH 86-63-60, April 22, 1966.

APPENDIX III

ANALYSIS OF COMPLAINTS CONCERNING POLLUTANT EMISSION BY AIRCRAFT

The investigation upon which this analysis is based was conducted by making contact with those agencies that are apt to receive complaints about air pollution or about aircraft. In the three metropolitan areas studied--Los Angeles, New York, and Washington, D.C.--these are the local air pollution control agencies and the airports. Other agencies such as local units of government tend to refer complaints to these agencies.

The Handling of Aircraft Air Pollution Complaints

The Los Angeles Air Pollution Control District receives (and files) complaints about "smog" from aircraft; however, it makes no direct use of these complaints in its abatement efforts. Rather than attempting to respond to complaints directly, the District maintains a program of aircraft engine research designed to reduce effluents. For example, tests are now being conducted to assess the effectiveness of fuel additives in reducing exhaust pollutants. Currently, the Los Angeles Air Pollution Board (County Board of Supervisors) has ordered a tightening of standards for aircraft emissions and of the enforcement of present standards (Ref III-1).

Los Angeles International Airport (LAX) receives complaints about aircraft, both in its Public Relations and Sound Abatement Departments. When the Sound Abatement Department receives a complaint about air pollution from aircraft, the complainant is referred to a study made by the Los Angeles Air Pollution Control District (Ref 3) showing that aircraft are minor contributors to the total amount of pollution.

In the Washington, D. C. area, responsibility for air pollution abatement is scattered among a number of city and county units in Maryland and Virginia, and the Air Pollution Control Division of the District of Columbia Department of Public Health. These agencies have recently adopted a uniform method for handling and recording air pollution complaints through their joint efforts in the Metropolitan Washington Council of Governments; 1968 will be the first full year using the new system.

Complaints about aircraft around Washington, D. C., center at the Federal Aviation Administration Bureau of National Capital Airports, which operates Dulles and National airports. No separate count is kept of complaints about air pollution from aircraft, but when people do not make such complaints, they are told that recent findings (Ref 120) show that aircraft account for less than 1 per cent of all air pollution.

In the New York City area, contact was made with the New York City Department of Air Pollution Control, but not with air pollution control agencies in neighboring counties of New York and New Jersey. The New York City Department indicates its records do not include any information about aircraft.

The Port of New York Authority, as operator of J. F. Kennedy, LaGuardia, and Newark airports, receives a majority of the complaints concerning aircraft in the New York City area. Telephone complaints to an airport are taken by the airport's sound crew; complaints, either by phone or by letter, which come directly to the Port Authority or are referred to it by another agency, such as the Mayor's office, are handled by the Authority's Aviation Public Service Division.

An Overview of Complaint Data

One characteristic of aircraft air pollution data is its inaccessibility. No air pollution agency that we contacted reports aircraft complaints as a separate category, and no airport reports air pollution complaints as a separate category. Aircraft are considered by many to be minor contributors to air pollution and air pollution is a minor reason for complaining about aircraft; hence, aircraft air pollution tends to be lightly regarded.

While we obtain no estimates of the magnitude of aircraft air pollution complaints for the Los Angeles area, the Air Pollution Control District did mention that persons who complain about smog from aircraft often complain about their noise also. The District of Columbia Air Pollution Control Division reported receiving two complaints about aircraft in 1967, while the Bureau of National Capitol Airports had received "a few" air pollution complaints. The New York City Department of Air Pollution Control reports no complaints about aircraft in their 1967 records. The Port of New York Authority received 26 complaints from 19 persons about air pollution from aircraft in 1967.

The Interpretation of Complaint Data

"Complaint data," that is, complaints on file, may not be a good representation of "complaints," even of official complaints. Complaints which go to an agency which has not instituted a complaint procedure or to an officer who may be outside the established complaint network, or which use a medium such as a personal visitation or a meeting, rather than mail or telephone, for which complaint routines have not been established, often never find their way to the files. Some files are never analyzed, and again, these tend to be those that fall outside the routines. Thus, "complaint data" not only may underestimate "complaint behavior," but may lead to misinterpretation.

Complaint behavior may not accurately represent the seriousness of the situation which engenders it. In the Boston area where airport complaint files are currently (November, 1968) under study, 88 complaints were recorded in the calendar year 1967, while 330 were recorded from January 1 to October 15, 1968. Air traffic has neither increased nor changed its pattern appreciably, but the senior United States Senator from the area held hearings about the airport early in the calendar year, a number of local office holders have interested themselves in the problems of nearby residents, and the airport itself has publicized its unlisted "complaint" telephone number for the first time in several years. Thus, increased hope of abatement and a known mode for complaining seem to have increased the number of complaints.

Characteristics of complainers may have similar effects. Longer residence in one's neighborhood and high occupational status (Ref III-2), more frequent exposure to mass communications, and a more urbane outlook on life (Ref III-3) seem to increase people's likelihood of complaining about air pollution. However, despite these sources of individual variation, complaints about air pollution are evoked by polluted air, and some relation may be expected to hold between the two.

Thus, meaning can be derived from a study of complaint data, but relations between complaint data and complaints, annoyance, community action, or the degree of environmental degradation are apt to be very complex. Hence, the data must be interpreted with great care, and a much more systematic study of the relations between complaints and background factors must be made before complaints can confidently be employed as social indicators of known significance and reliability.

The Significance of Aircraft Air Pollution Complaints

In assessing the significance of complaints about air pollution from aircraft, it must be recognized that no complaints are to be expected concerning emission of invisible and nonodorous pollutants. The public is not directly aware of the quantities of CO, organics, or NO_x emitted by aircraft, or of the contribution by aircraft to community pollution levels. Consequently, complaint analysis is not an effective approach to evaluating the impact of these emissions on the community.

On the other hand, the public is aware of odor and visible smoke emission by aircraft. Since the principal effects of these emissions are offenses to the senses, complaints directed at these effects might well be regarded as a significant measure of impact. This study of complaint data has revealed that the number of complaints about air pollution from aircraft is very small in comparison to complaints about other sources. Consequently, despite the caveats entered above about the interpretation of complaint data, we feel safe in concluding that the sensory effects associated with aircraft exhaust emissions are not of pressing concern to the public.

REFERENCES

III - 1 Los Angeles Times, September 16, 1968.

III - 2 Medalia, "Community Perception of Air Quality", U. S. Department of Health, Education and Welfare, Public Health Service, Division of Air Pollution, Cincinnati, Ohio, Report #999-AP-10, 1965.

III - 3 Van Arsdol, "Social Organization and Air Pollution", Paper presented at meeting of the Air Pollution Control Association, Cleveland, Ohio, June, 1967.